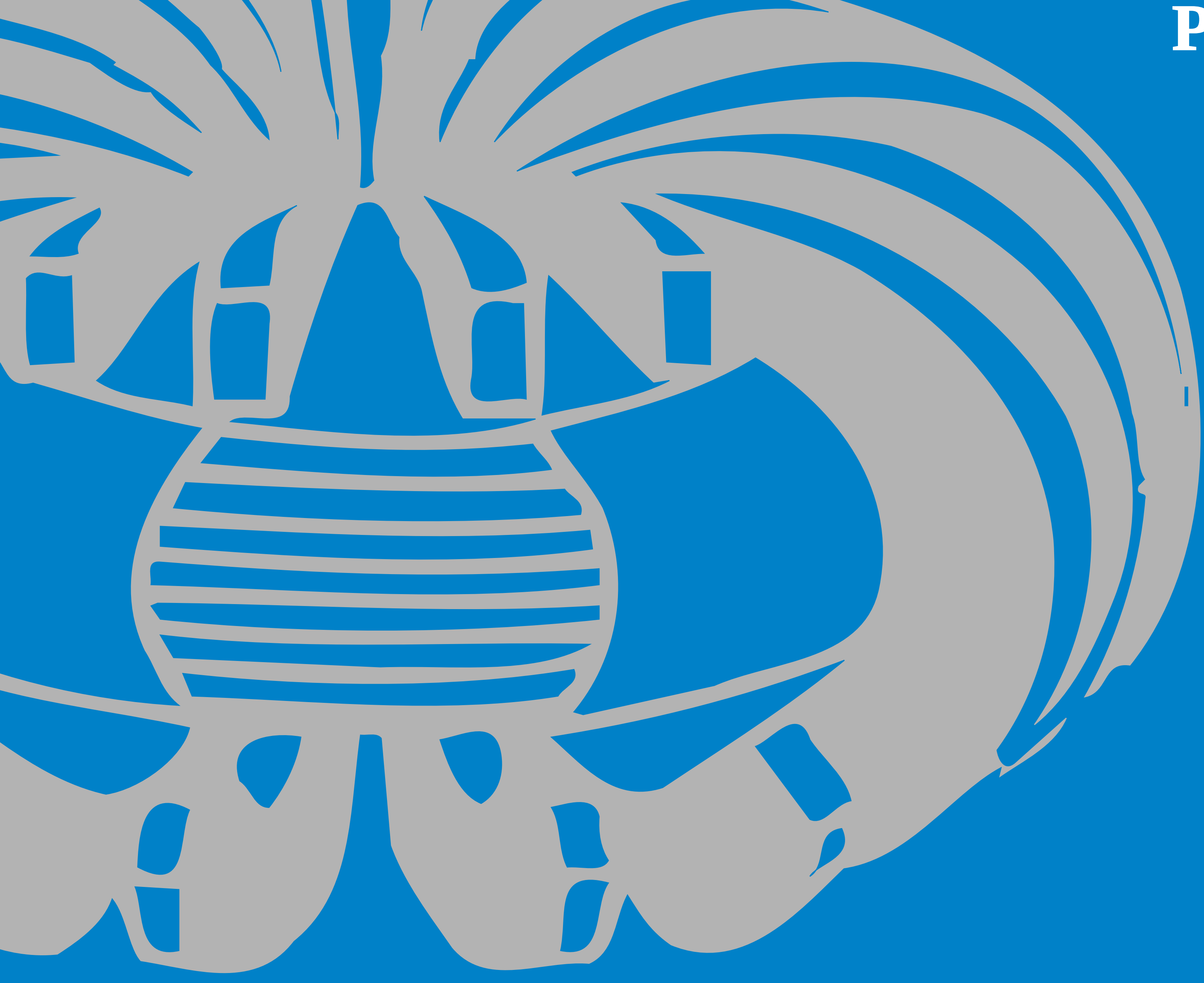

Program as a Source of Technology Transfer

September 1993

U.S. Department of Energy
Office of Energy Research
Office of Fusion Energy

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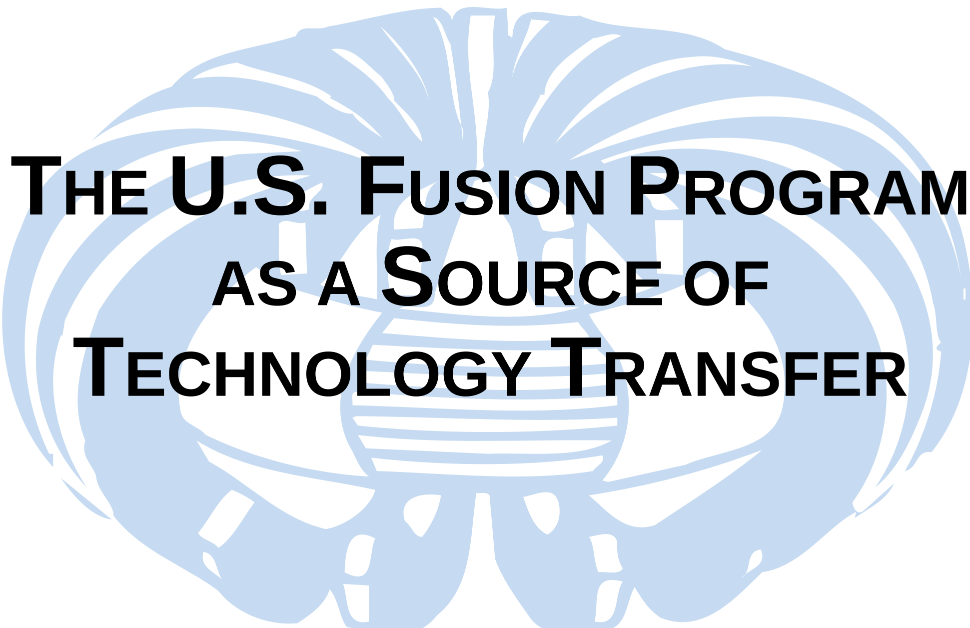
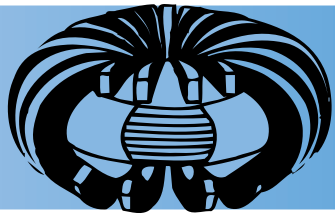


THE U.S. FUSION PROGRAM AS A SOURCE OF TECHNOLOGY TRANSFER

September 1993

U.S. Department of Energy
Office of Energy Research
Office of Fusion Energy



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THE BENEFITS OF FUSION

FORGING LINKS WITH INDUSTRY

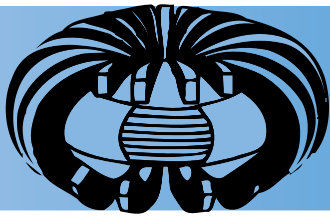
Under the sponsorship of the U.S. Department of Energy, the magnetic fusion energy program carries out theoretical and experimental research aimed at harnessing the process that powers the sun—nuclear fusion. In the course of this work, which extends from basic science to high technology, fusion researchers integrate and apply scientific and technical knowledge from a broad range of fields.

The innovative solutions that they have developed in addressing the challenges of fusion power have in turn produced new science and technology with applications that benefit many areas beyond the fusion program. While making great strides toward the practical harnessing of fusion energy in electric power plants, which is expected in the first half of the 21st century, the magnetic fusion program has produced ideas, innovations, and techniques that are directly applicable to areas as diverse—and important—as environmental protection and remediation, aerospace, national defense, manufacturing, materials, computing and electronics, health and medicine, and transportation.

Technology transfer to industry is an important part of the mission of the Department of Energy. Mechanisms for technology transfer and other programs through which industry can participate in fusion research are discussed in detail in this document, and examples of technology transfer in which the fusion program was the principal or a significant contributor are described. Also included are examples of current fusion technology development with significant potential for transfer to industry in the immediate future.

The issues addressed in the magnetic fusion program, from basic electromagnetic phenomena to the development of fusion power plants, are issues that have demonstrated their potential for applications across America's technology base. Further advances in the program, culminating in the achievement of fusion power as a clean and abundant energy source, should lead in their turn to attractive dividends along the way.

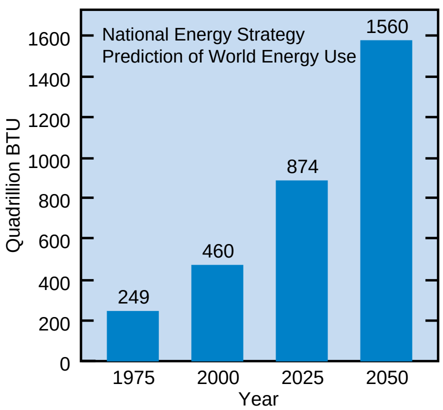
N. Anne Davies
Associate Director for Fusion Energy
Office of Energy Research
U.S. Department of Energy



FUSION ENERGY

THE PROCESS AND THE PROMISE

Nuclear fusion—the process that powers the stars—is the joining of the nuclei of light atoms, such as those of hydrogen, to form a heavier atom. This process releases much more energy than is needed to make the reaction occur. As the world's energy needs have increased, the limits of its resources are becoming apparent. Fusion energy offers the promise of becoming a safe, economical, abundant, and environmentally acceptable source of power. While the technological challenges of harnessing fusion power are large, significant advances have been and continue to be made.



Why Do We Need Fusion Energy?

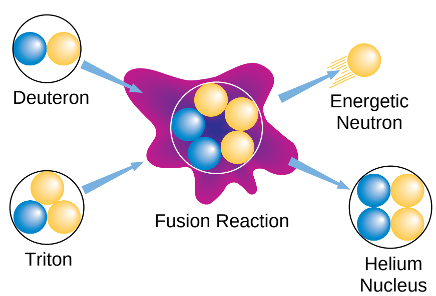
Estimates of the need for energy in the future take into account population growth and increasing urbanization and industrialization throughout the world. Some predictions indicate that about four times as much energy will be needed by the year 2050 as is used today.

The principal sources of this energy include fossil fuels (coal, gas, and oil), nuclear fission fuel, and various forms of solar energy. For all of these sources, varying degrees of uncertainty exist and will continue to exist regarding the extent and security of fuel reserves, environmental effects, plant availability, and economic cost. Fusion energy, while not devoid of some of these uncertainties, has significant potential to become an important addition to the mix of energy sources that will be required to satisfy the energy needs of future generations throughout the world.

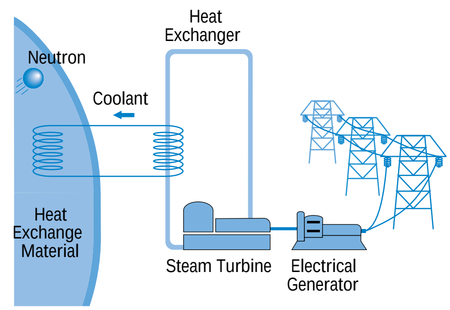
How Does Fusion Energy Work?

In nuclear fusion, the nuclei of light atoms combine, or fuse, to form the nucleus of a heavier atom. The new nucleus is lighter than the original two, and the "extra" mass is released as energy according to Einstein's famous equation, $E = mc^2$. In the sun, hydrogen is converted into helium through a series of fusion reactions, and the energy is released in the form of sunlight.

In the reaction most likely to be used in the first fusion power plants, the nuclei of two isotopes of hydrogen, deuterium and tritium, fuse and create the nucleus of a helium atom (also called an alpha particle) and a neutron. Most of the energy of the reaction is carried by the neutron.



In a fusion reactor, neutrons would be absorbed by a surrounding "blanket" that would convert their energy to heat. This heat would be used to generate steam for driving an electric turbine generator. The fusion energy that could be released by a single gram of deuterium-tritium fuel equals the energy from about 2400 gallons of oil.



What Are the Advantages of Fusion Energy?

Fusion is a potential alternative source of power that has several advantages:

- Deuterium fuel is not radioactive and occurs naturally in water. The supply of this fuel is widely available, virtually unlimited, and free from foreign interdiction, and shipment is routine.
- Tritium, the other principal fusion fuel, is radioactive, but it can be manufactured directly within a fusion reactor plant, through the reaction of fusion neutrons with lithium, which is an abundant element.
- No fission by-products are produced. The fusion reaction waste product, or "ash," is helium, which is not radioactive.
- Structural radioactivity will occur in metallic components inside a fusion reactor, but the lifetime of the radioactivity can be reduced by using "low-activation" materials.

- Fusion has safety advantages. Only a small quantity of fuel is located in the reaction chamber at any time. If a malfunction were to occur, any inadvertent release of energy and fuel would also be small.
- Advanced fusion reactors may be able to use only deuterium or other nonradioactive materials as fuel.

For these reasons, although the demonstration of economical power generation from fusion is perhaps one of the most difficult scientific endeavors ever undertaken, nuclear fusion offers great promise to become part of the long-term solution to the world's need for energy.

How Is Fusion Power Produced?

In addition to the three common states of matter—solid, liquid, and gaseous—there is a fourth state called a "plasma." At high enough temperatures, matter is ionized; that is, the electrons of its atoms are stripped away from the nuclei. The resulting mixture of electrons and atomic nuclei is known as a plasma. The nuclei, or ions, carry a positive electrical charge, and the electrons carry a negative electrical charge.

The charged particles in a plasma interact with magnetic fields in a way that causes them to rotate around magnetic field lines, much as iron filings are drawn into patterns by a magnet. Particles can move freely along magnetic field lines, traveling in a spiral, or helix, through a magnetic field. With careful design, it is possible to create "magnetic bottles," or config urations, that can effectively confine plasmas.

One of the most efficient mag netic configurations is a doughnut shape, or torus. Most magnetic con- finement research today is focused on a toroidal configuration called the tokamak, invented in Russia in the 1950s. The name "tokamak" is derived from the Russian words for "torus," "chamber," and "magnetic."

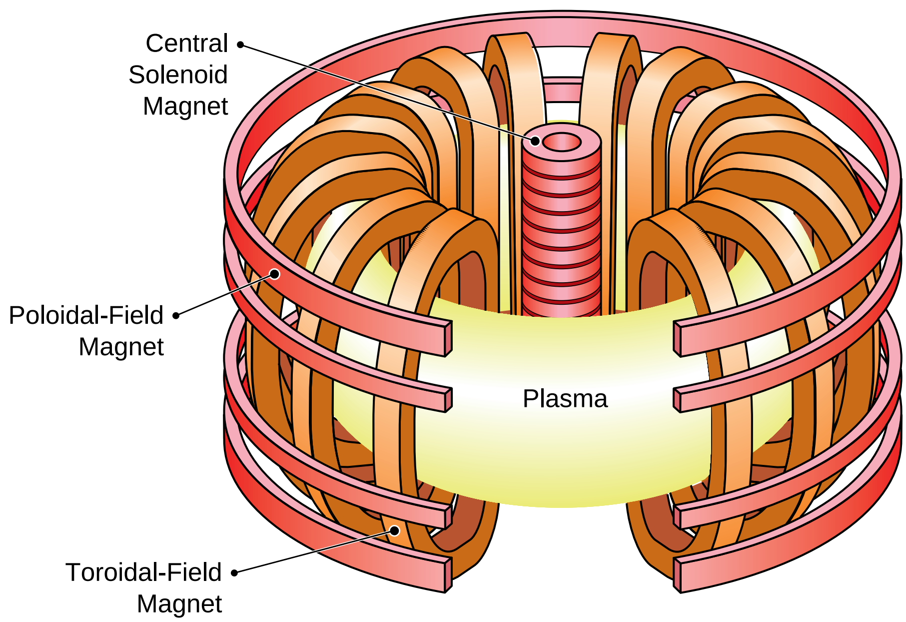
The magnetic fields that confine the plasma in a tokamak are generated by powerful electro magnets, as shown below. By care fully adjusting the currents in these electromagnets, fusion scientists can control the plasma in the proper configuration.

Tokamaks have come the closest to simultaneously achieving the con ditions under which fusion fuel will react and produce significant energy. These conditions, which have been met individually, are as follows.

- The fusion fuel must be heated to very high temperatures. The tem perature needed for the fusion of deuterium and tritium is about 100 million degrees Celsius. At this temperature, the reacting particles have enough energy to overcome the electrostatic repulsion between particles with the same charge, so they can come close enough to fuse.
- The plasma must be dense enough (that is, the number of particles in the fusion plasma must be high enough) for significant power to be produced.
- The fuel must be contained so that it holds its energy long enough for the fusion reactions to occur and a net release of energy to take place.

Intensive programs in the areas of plasma physics and fusion tech nology have demonstrated the scientific feasibility of fusion. Current efforts are directed toward a combined demonstration of fusion's scientific and technological feasibility. Design studies are directed toward developing power plants that will produce electricity economically, reliably, and safely.

As with most scientific endeavors, the greatest challenges hold the greatest promise. Fusion research, with its goal of producing abundant energy to meet human needs, is one of the most chal lenging—and potentially most rewarding—areas of research today.



FUSION ENERGY

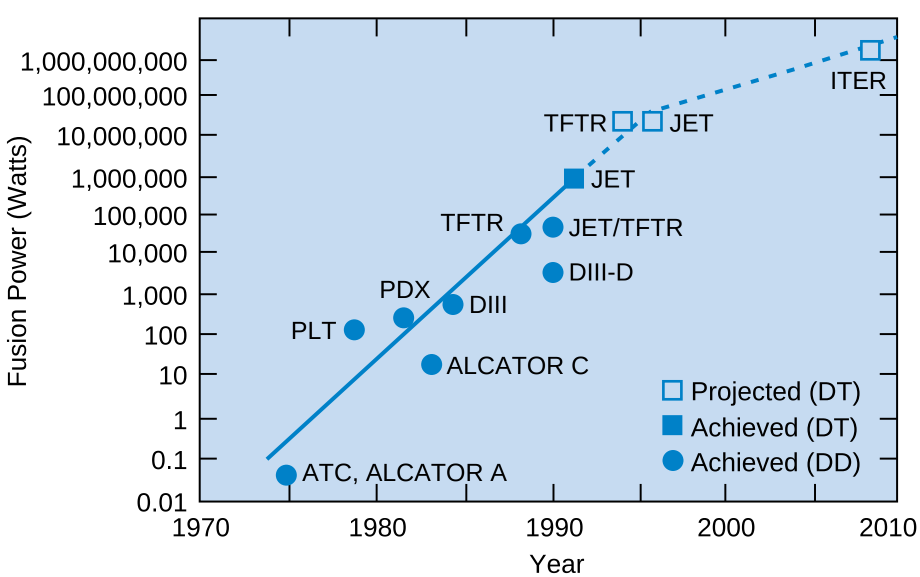
THE PROGRAM AND THE PAYOFFS

Research aimed at controlling the nuclear fusion process has been under way since the 1950s. In the course of a broad program focused on understanding the fusion process and applying the results to the development of power-producing reactors, fusion researchers have made significant contributions to basic scientific understanding and to high-technology development. Some of their more significant contributions are identified in this document.

Fusion research in the United States began in 1951, when the U.S. Atomic Energy Commission estab lished a secret program called Project Sherwood to investigate the feasibility of using a controlled fusion reaction to generate power. Magnetic fusion research was declassified in 1958, and scientists throughout the world began sharing the results of their work.

Steady advances toward the goal of useful fusion power have been produced through a broadly collabo -rative program that draws on the resources of research laboratories, industry, and universities in the United States and throughout the world.

Advances In Fusion Power



JET	Joint European Torus
ITER	International Thermonuclear Experimental Reactor
DIII & DIII-D	General Atomics
ATC, PLT, PDX, & TFTR	Princeton Plasma Physics Laboratory
ALCATOR A, C	Massachusetts Institute of Technology

The U.S. magnetic fusion pro gram is overseen by the Office of Fusion Energy in the Department of Energy's Office of Energy Research. With an annual budget of more than $300 million, the program focuses on developing the theoretical, experimental, and technological base for a fusion energy source.

This program is also producing benefits in other areas. Innovative solutions to issues that must be addressed in the process of making fusion power a reality are being extended to related areas of science and technology, producing unexpected dividends.

Why is the magnetic fusion pro gram, with its seemingly esoteric aim of confining very hot matter within magnetic fields, already a rich source of valuable spin-offs, years before it is expected to reach its primary goal?

The answer to this question can be found by considering the scope and aims of the magnetic fusion research program. Fusion scientists are dealing directly with the same fundamental force of nature—electromagnetism—that has given rise to applications such as electric power, wireless communications, and electronics.

Fusion scientists deal with very energetic matter in the presence of strong electromagnetic fields. They investigate the collective behavior of charged particles in electric and magnetic fields. This field of study is called plasma physics, and its fundamental principles can be applied to subjects ranging from the behavior of stars to microwave cooking.

Fusion researchers integrate the theory and models developed through studies of plasma physics with technology development in high-power heating and fueling sys tems, superconducting magnets, and advanced materials to design and operate fusion experiments. Many of these technologies deal with phe nomena that are applicable to areas that lie beyond fusion.

Technology Transfer

Mission and Mechanisms

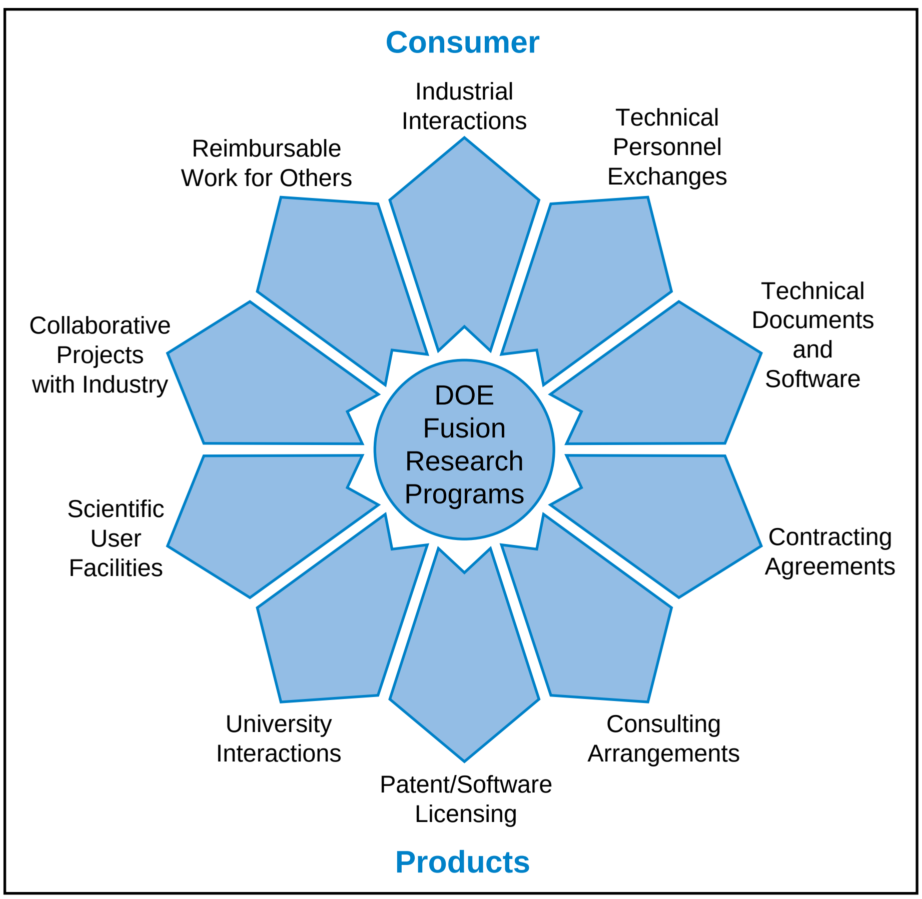
The fusion research institutions of the U.S. Department of Energy (DOE) possess skills, facilities, and technologies that represent a unique set of resources for enhancing the nation's competitiveness. In support of DOE's mission to transfer technology to industry, consumers, and other end users, these institutions provide access to their resources through a variety of mechanisms.

The development and application of advanced technology are of critical importance for U.S. competitiveness in world markets. The Department of Energy (DOE), which supports a wide range of research and development (R&D) activities through its world-class laboratories and through university programs, is working to transfer the results of these activities to industry, consumers, and other end users.

The fusion research institutions supported by DOE represent a particularly strong resource for technology transfer. The interdisciplinary teams of experts assembled to attack the problems posed by magnetic fusion have generated innovative techniques, devices, and skills that are directly applicable to the solution of complicated problems in other areas, as described in this document, and the experts themselves are also a resource.

Access to these capabilities is available through a number of mechanisms, including

- collaborative projects with industry, including cooperative R&D agreements, or CRADAs,
- technology and software licensing,
- scientific user facilities,
- industrial interactions,
- technical personnel exchanges,
- reimbursable work for others,
- consulting arrangements,
- university interactions,
- contracting agreements, and
- technical information and software.



Collaborative Projects with Industry

Increasing the number and scope of collaborative R&D projects with U.S. industry is one of the most important goals of current DOE technology transfer efforts. The CRADA is a relatively new tool for sharing laboratory facilities, technologies, and expertise with industry and universities. The terms of a CRADA are flexible, so that each agreement can be customized to provide optimum leveraging of resources and sharing of complementary capabilities, including funds, personnel, services, facilities, and equipment.

Technology and Software Licensing

Each laboratory licenses its own patents, under terms and conditions tailored to the specific situation. Information on computer software, which is copyrighted and licensed by laboratory contractors, is available from the Energy Science and Technology Software Center in Oak Ridge, Tennessee. Technologies may be licensed from the laboratories on a fully exclusive basis or (more often) a nonexclusive basis. Licensing represents a relatively low-risk method of accessing new technology developed by the national laboratories.

Scientific User Facilities

Scientific user facilities, including several fusion facilities, are available to university and industrial researchers for approved projects. Potential user research proposals are reviewed for appropriateness and quality, and access to a facility is based on the scientific merit of the proposal. Traditionally, if users pub lish the results of their work, there is no charge for using the facility; if the work is proprietary, users pay the full cost of using the facility, and results are not published. Patent rights to inventions are generally given in advance to users paying full costs.

Industrial Interactions

Several methods are used for inter actions with private industry. Some interactions occur on a program-specific basis, others through confer ences and workshops sponsored by the laboratories. DOE and its labora tories are major participants in and supporters of the Federal Laboratory Consortium, which focuses on facili tating increased interactions between U.S. industry and federal laboratories. Events sponsored by the Industrial Research Institute and interaction with state and local governments are other mechanisms for industrial interactions.

Technical Personnel Exchanges

Personnel exchanges with U.S. industries and universities are an important component of DOE tech nology transfer efforts. Exchanges may be conducted through specific R&D programs or arranged on an informal basis with the laboratories.

Reimbursable Work for Others

The DOE fusion research facilities are available to perform work for industry or other federal agencies as long as the work

- pertains to the fusion mission,
- does not adversely affect the achievement of program require-ments, and
- does not directly compete with capabilities available in the private sector.

A patent waiver can be obtained from DOE to give ownership of any inventions resulting from the research to a participating company.

Consulting Arrangements

Scientists and engineers at DOE fusion research institutions are avail able to consult in their areas of tech nical expertise. Each contractor has its own consulting practices; staff members are generally free to nego tiate contracts for consulting and can sign nondisclosure agreements.

University Interactions

Support for the training of the next generation of scientific and tech nical leaders is provided in several ways. DOE provides funds for graduate students and post-doctoral research fellows at universities and at fusion research institutions. Ongoing research and education programs bring faculty, undergraduate students, and precollege science teachers and stu dents to DOE's fusion research insti tutions. Increasing emphasis is being placed on reaching minority and women students through educational outreach and training programs.

Research collaborations among university, private-sector, and federal scientists take place throughout the fusion program by means of formal collaborative agreements, admini-strative procedures for large-scale computing, and joint appointments of scientists.

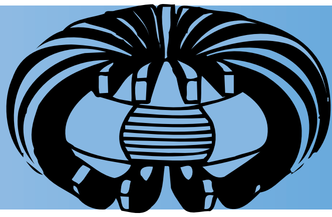
Contracting Agreements

Subcontracts, hardware procure ments, and (less frequently) grants are used by DOE's fusion research institutions to work with industry and universities. These contracting agreements offer an opportunity for the private sector to participate in the development of new technology, as well as facilitating more effective communication between the participants.

Technical Information and Software

Technical documents and data-base software are traditional means of disseminating information on research results and technologies available at fusion research institu tions. Copies of reports originating at DOE fusion research institutions are submitted to DOE's Office of Scientific and Technical Information (OSTI) in Oak Ridge, Tennessee, and to the National Technical Information Center in Springfield, Virginia. OSTI also compiles and maintains databases and computer software to assist individuals in deter mining the types of technical activities conducted by DOE research laboratories.

The National Technology Trans fer Center in Wheeling, West Virginia, represents a new resource for potential technology users. By dialing the Center's toll-free telephone number (1-800-678-NTTC), technology users can access an index to all federal technology databases.



TECHNOLOGY TRANSFER

CAPABILITIES AND CONTACTS

Information on fusion technology and science, specific developments, and fusion research is available from the U.S. Department of Energy (DOE) and from its fusion research institutions. Major fusion institutions and capabilities are listed here.

Office of Fusion Energy
Office of Energy Research
U.S. Department of Energy
Washington, DC 20585
Technology transfer contact:
Mr. Warren A. Marton
(301) 903-4965

- Promotion of industrial participation in the fusion pro gram, both in developing the science and technology needed for fusion and in applying the results to areas outside fusion

Argonne National Laboratory (ANL)
9700 South Cass Avenue
Building 9000
Argonne, IL 60439
Technology transfer contact:
Dr. Paul Betten
(708) 252-4962

- Materials, magnets, remote maintenance, electromagnetics, magnetohydrodynamics, instru mentation and measurement
- High-Temperature Superconductivity Pilot Center

General Atomics, Fusion Group (GA)
P.O. Box 85608
San Diego, CA 92186-9784
Technology transfer contact:
Mr. Chris J. Hamilton
(619) 455-3364

- Plasma processing, magnet technology, pulsed power systems, high-power microwave and rf systems, advanced materials, accel erator technology, space physics, supercomputing and computational science

Idaho National Engineering Laboratory (INEL)
P.O. Box 1625
Idaho Falls, ID 83415
Technology transfer contact:
Mr. Richard E. Hitt, Jr.
(208) 526-9353

- Thermal-hydraulics, fluid modeling and computing
- Safety research and instrumentation

Lawrence Berkeley Laboratory (LBL)
Berkeley, CA 94720
Technology transfer contact:
Ms. Cheryl Fragiadakis
(510) 486-6467

- Plasma and ion sources, surface modification of materials, accelerator and neutral beam technology

Lawrence Livermore National Laboratory (LLNL)
P.O. Box 808
Livermore, CA 94551
Technology transfer contact:
Mr. Gilbert R. Marguth
(510) 422-6416

- Scientific and engineering software, precision engineering, advanced materials, laser technology
- National Energy Research Supercomputer Center

Los Alamos National Laboratory (LANL)
P.O. Box 1663
Los Alamos, NM 87545
Technology transfer contact:
Dr. Ronald E. Barks
(505) 665-2133

- Advanced manufacturing and materials, aerospace, high-performance computing
- High-Temperature Superconductivity Pilot Center

Massachusetts Institute of Technology (MIT)
Plasma Fusion Center
167Albany Street
Cambridge, MA 02139
Technology transfer contact:
Dr. Dan R. Cohn
(617) 253-5524

- Superconducting magnets and high-performance copper magnets, gyrotron development, application of plasma treatment to waste

Oak Ridge National Laboratory (ORNL)
P.O. Box 2009
Oak Ridge, TN 37831-8218
Technology transfer contact:
Mr. Larry M. Dickens
(615) 576-9682

- Energy storage, environmental protection and remediation, defense, aerospace, manufacturing, materials, computing and electronics
- High-Temperature Superconductivity Pilot Center

Princeton University
Plasma Physics Laboratory
(PPPL)
P.O. Box 451
Princeton, NJ 08543
Technology transfer contact:
Dr. Lewis D. Meixler
(609) 243-3009

- Neutral beam technology, remote handling, plasma engineering and diagnostics, surface modification technology, computer systems, instrumentation and measurement, soft X-ray development, aerospace

Sandia National Laboratories
(SNL)
SNL/New Mexico
P.O. Box 5800
Org-4201
Albuquerque, NM 87185
Technology transfer contact:
Mr. Olen D. Thompson
(505) 271-7822
SNL/California
P.O. Box 969
Livermore, CA 94551
Technology transfer contact:
Dr. T. Michal Dyer
(510) 294-2678

- Plasma-material interactions; high heat flux testing; plasma diagnostics and modeling

Matrix of Fusion Technology Areas and Major Fusion Institutions

	ANL	GA	INEL	LBL	LLNL	LANL	MIT	ORNL	PPPL	SNL
Magnetics and superconductivity	●	●			●	●	●	●	●	
Plasma production		●		●			●	●	●	●
Materials development	●	●	●		●	●		●		●
Fuel cycle						●		●		
Microwave and rf heating		●			●		●	●	●	
Ion and neutral beams		●		●		●		●	●	
Power systems		●			●		●	●	●	●
Instrumentation and measurement	●	●	●	●	●	●	●	●	●	●
Fusion theory and computing	●	●	●		●	●	●	●	●	
Plasma confinement devices		●				●	●	●	●	
Safety and waste management			●				●			

PLASMA CONFINEMENT FACILITIES

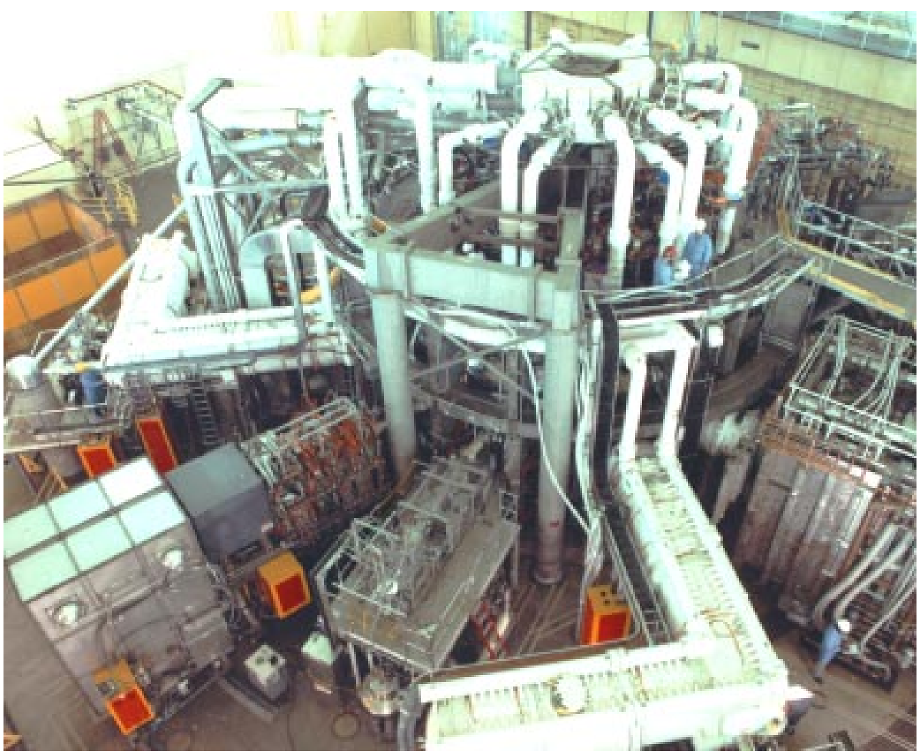
INDUSTRIAL INVOLVEMENT

At the heart of the magnetic fusion program are the facilities in which experiments are performed by fusion researchers. These facilities, located at national laboratories, at universities, and in industry, are the products of a continuing interchange between the fusion research community and industry. The complex task of designing, fabricating, and constructing fusion facilities has involved the transfer of technology from the fusion program to industry and has required the development of new industrial skills with applications both within and beyond fusion. Industry is positioned to continue and expand this relationship in the construction of the next generation of fusion experiments.

Since the initiation of magnetic fusion research in the 1950s, the fusion knowledge base and the understanding of plasma behavior have steadily expanded. This progress has occurred through research on increasingly sophisticated plasma confinement facilities, in which new theories are tested, new technologies are launched, and new insights are obtained. The success of these facilities is due in large part to the accomplishments of the nation’s industries.

Today’s plasma confinement facilities are equipped with all of the necessary systems for production, control, and analysis of plasmas with properties approaching those needed for a fusion reactor. The designs for new facilities, in which the scientific and technological feasibility of fusion power will be demonstrated, are now on the drawing boards—or, more accurately, in the memories of computer-aided design systems.

Examples of past and present facilities include the Tokamak Fusion Test Reactor (shown below) and the Princeton Beta Experiment, both at the Princeton Plasma Physics Laboratory; the DIII-D tokamak at General Atomics; Alcator C-Mod at the Massachusetts Institute of Technology; the Mirror Fusion Test Facility at Lawrence Livermore National Laboratory; the Advanced Toroidal Facility at Oak Ridge National Laboratory; and the Texas Experimental Tokamak at the University of Texas.



A common theme associated with all of these facilities is that industrial involvement has been essential to their success. Levels of involvement have varied among facilities; industry’s contributions have included industrial system integration; hardware design, fabrication, and installation; research and development; building design and construction; and system testing.

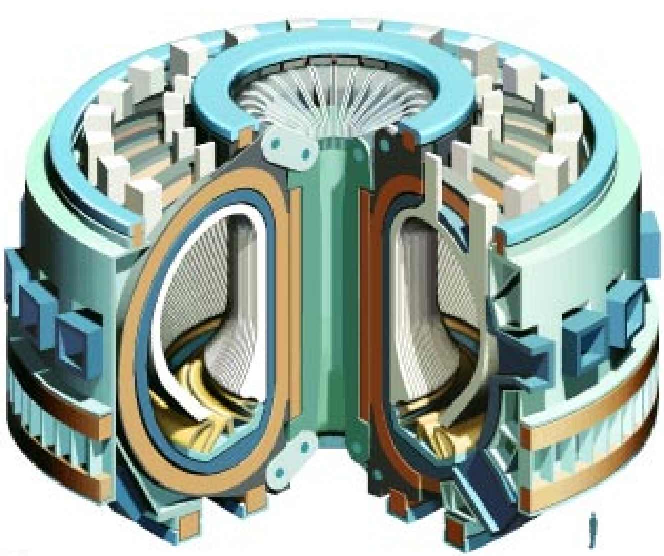
Examples of companies in the United States that have contributed to fusion research include Bechtel, Ebasco, General Dynamics, Grumman, Hughes, McDonnell Douglas, RCA, TRW, Varian, and Westinghouse. General Atomics has an organizational unit that is devoted solely to fusion research and development. In the course of the fusion program, new companies have been established to take skills gained in the program to a larger market.

Looking to the future, a new facility, the superconducting Tokamak Physics Experiment (TPX), is now in the conceptual design phase. Industrial involvement is an essential part of this phase, and industry's role will expand significantly if construction is authorized.

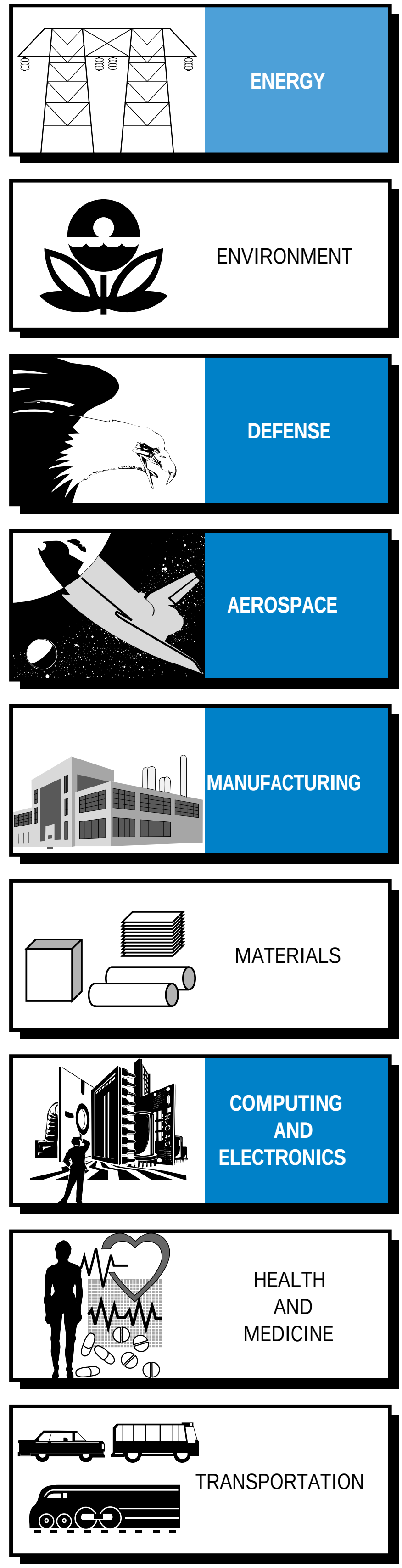
Industry is also participating in the International Thermonuclear Experimental Reactor (ITER) project, a major initiative by the United States, Japan, the European Community, and the Russian Federation that recently entered the design and technology development phase. For this six-year phase, called the Engineering Design Activities (EDA), scientists and engineers representing the four parties are forming a Joint Central Team (JCT) located at design centers in San Diego, California; Garching, Germany; and Naka, Japan. The JCT will integrate the ITER engineering design and technology development to be carried out by the "home teams" of the four parties. These home teams include both laboratory and industrial participants. The decision on whether and where to construct ITER depends in large part on results obtained during the EDA.

Broad industrial involvement is being arranged with the aim of preparing industry to bid successfully on the construction of ITER. In the United States, industrial teams have been selected in the technical areas of magnets, blankets, plasma-facing components, vacuum vessel, and remote handling. These teams carry out specific technology development tasks assigned to the United States. In addition, an industrial design group will be selected to carry out design tasks assigned to the United States. Each of the industry teams will work closely with a lead U.S. fusion institution to accomplish the transfer to industry of technology that is now resident in fusion laboratories and universities.

The technology and skills that will be transferred to industry through these projects should position industry to compete for future fusion business, both in the United States and in the international marketplace. As advances continue toward the ultimate goal of fusion research—the application of fusion power to the production of energy—the partnership between the fusion research community and industry should become even stronger and broader.



ITER



MAGNETICS AND SUPERCONDUCTIVITY

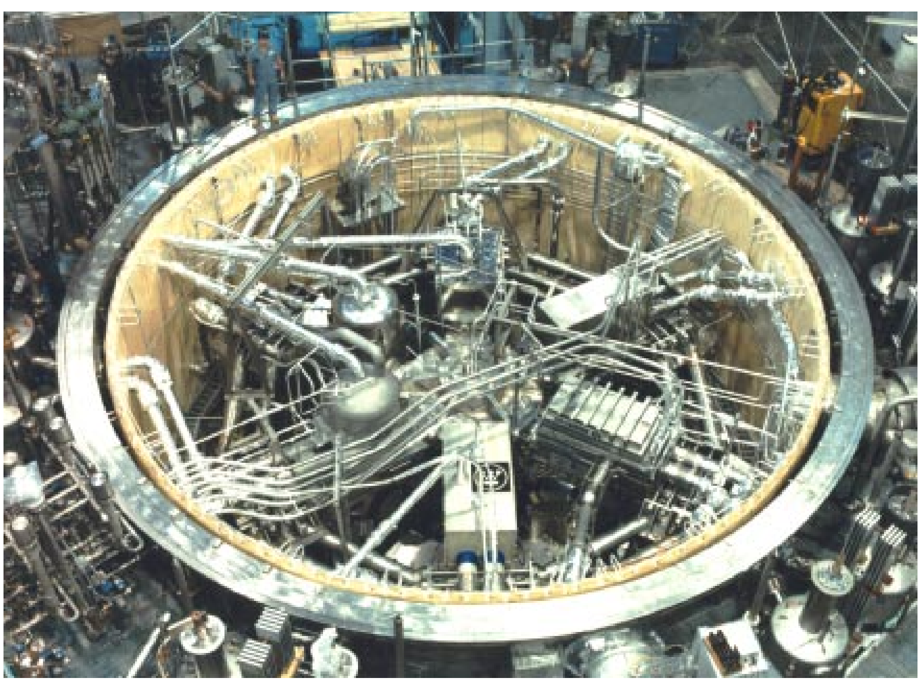
THE BIG CHILL

The magnetic fields needed to confine a fusion plasma are about 200,000 times more powerful than the magnetic field at the earth's surface. Progress in magnetic confinement fusion has been built on magnet research and development, much of which has been carried out in collaborative programs with industry.

Superconductivity—the property of some materials that allows them to carry electrical currents with virtually no resistance—is essential to the economical generation of fusion power. Superconducting magnets on a scale comparable to that needed for a fusion reactor were first demonstrated in an international collaboration between the fusion research community and industry. Industry is now applying the experience gained from this collaboration to design high-field magnets for future fusion experiments. Expertise with low-temperature superconductors, which operate at temperatures near absolute zero, is contributing to the development of a new class of materials that are superconducting at much higher temperatures. The national laboratories and industry are working together on practical applications in areas other than fusion, such as energy storage and conservation, aerospace, manufacturing, health and medicine, and transportation.

Materials that remain supercon ducting in the presence of strong magnetic fields were discovered in the early 1960s. By the early 1970s, fusion reactors with supercon-ducting magnets, or coils, were being proposed.

Development work led to the Large Coil Task (LCT), a program that involved technology transfer and industrial partnerships on an international scale. Six large coils, each weighing about 45 tons, were placed in the International Fusion Superconducting Magnet Test Facility (shown below) and tested to 9 tesla by an international team of researchers. These coils were designed, developed, and manu factured by three companies in the United States and by one each in the European Community, Japan, and Switzerland. By demonstrating the integration of large-scale, advanced-technology components that were cooperatively designed and pro-duced by a team of industrial partners, the LCT paved the way for further collaborations and tech-nology transfer on a broad scale.



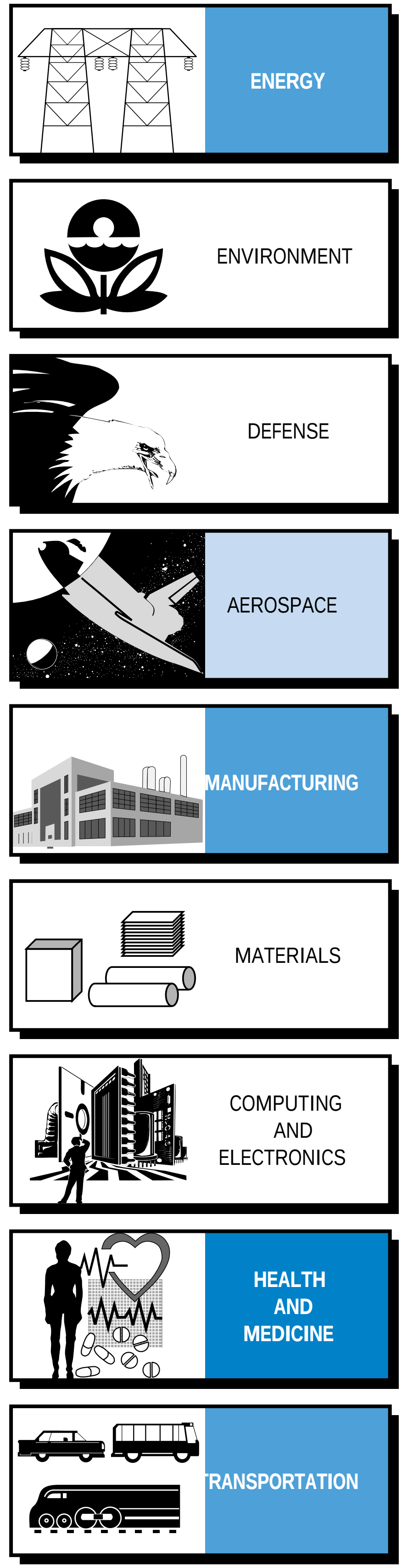
Companies such as General Dynamics and Westinghouse, which developed their magnet manufac turing capabilities in support of fusion projects such as the LCT, the ELMO Bumpy Torus, and the Mirror Fusion Test Facility, are supplying magnets for the Super conducting Super Collider, a high-energy physics experiment, and developing the 13-tesla supercon ducting coils for the International Thermonuclear Experimental Reactor (ITER).

The materials used to date in fusion magnets are superconducting only at temperatures near absolute zero. In 1986, a new class of materials that are superconducting at much higher temperatures was dis covered. To accelerate the development of these high-temperature superconducting (HTSC) materials, the Department of Energy established High-Temperature Superconductivity Pilot Centers at Argonne National

Laboratory, Los Alamos National Laboratory, and Oak Ridge National Laboratory. Through these pilot centers, which facilitate collaborations with industry, magnet researchers are applying expertise from what has come to be known as "low-temperature superconductivity" to the development of HTSC materials. Many of these researchers have a background in fusion magnetics.

The successful operation of the pilot centers provided the model for a new mechanism for technology transfer, the cooperative R&D agreement (CRADA). Both large companies (e.g., Corning, DuPont, General Electric, IBM, and Westinghouse) and small companies (e.g., American Magnetics, American Superconductor; HiTc Superconco, and Superconductivity, Inc.) are involved in CRADAs covering a range of superconductor applications. Many of these participants also have "roots" in the fusion program.

Today, applications of superconductivity are being pursued well beyond the fusion program. Superconducting magnets are being evaluated for magnetically levitated (maglev) trains and for advanced propulsion systems with aerospace applications. Energy storage systems are being developed from low-temperature metallic superconductors that have long been part of the fusion program and from the new HTSC ceramic oxides. A highly efficient motor, pictured below, has been demonstrated with low-temperature superconductor and is ready to be adapted to HTSC materials. Because 64% of the electricity generated today is consumed by large electric motors, this motor could save billions of dollars per year. Frictionless magnetic bearings, magnetic refrigerators, more efficient medical diagnostic and process control systems, and low-loss power transmission cables are among the other applications under development.



Plasma Production

In the Chips

A plasma is an ionized gas—that is, a gas heated to temperatures at which its atoms dissociate into charged particles (ions and electrons). Producing a plasma is perhaps the most basic step in the magnetic confinement process. Methods developed by fusion researchers to produce, monitor, and control plasmas have wide utility outside the fusion program.

Plasma etching is a critical step in the fabrication of very small (submicron-scale) integrated circuits that are used in computers, communications equipment, and consumer electronics. Another important step in the fabrication process is plasma deposition, which is used to deposit thin films of insulators, conductors, and semiconductors. Plasmas are also used for cleaning and oxidizing surfaces.

The technology developed to monitor the parameters of fusion plasmas is directly applicable to plasma processing technology. Analysis of the fundamental chemical and physical processes occurring in plasmas has yielded a detailed understanding of these mechanisms that has led to improved performance in both fusion and industrial plasmas.

Plasmas are sometimes called "the fourth state of matter" because their properties are quite different from those of solids, liquids, or ordinary gases. Fusion scientists have studied these properties in detail, and their knowledge supports plasma applications in many areas outside fusion research.

Plasma processing is a broad term for the use of plasmas to modify the surface of materials. It is used in several of the largest manufacturing industries, and the number of applications is growing.

In the electronics industry, plasma etching is replacing chemical techniques for producing microchips from silicon wafers like the one in the photo at left. Plasma processing is the principal manufacturing technology for creating microelectronic devices on the very small (submicron) scale that is required for the advanced integrated circuits in computers, communications equipment, and consumer electronics products.

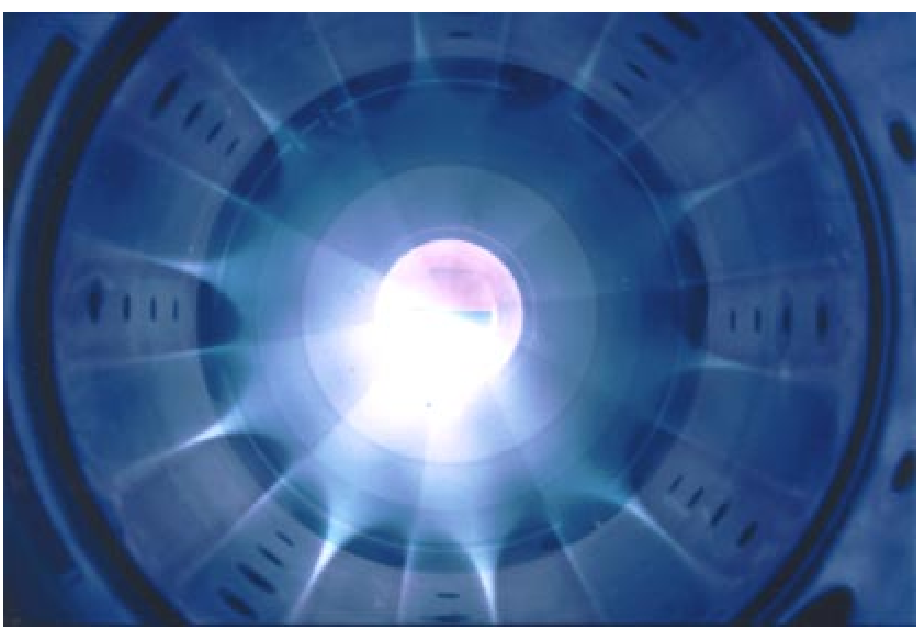
SEMATECH, a consortium of microelectronic manufacturers and the U.S. Advanced Research Projects Agency, is working to ensure that America stays at the forefront of the electronics manufacturing industry. Fusion scientists at national laboratories and universities, including Oak Ridge National Laboratory (ORNL) and Princeton Plasma Physics Lab oratory (PPPL), are involved in the development of advanced plasma systems and processes for the fabri cation of future microelectronic devices.

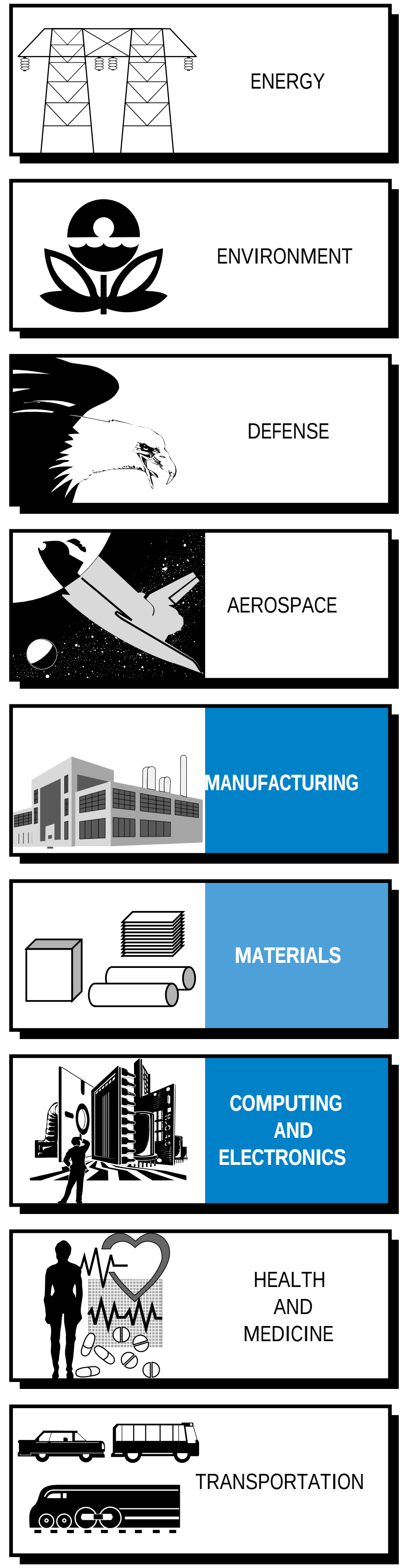
Electron cyclotron resonance heating (ECH) was one of the first techniques used by fusion researchers for plasma formation and heating, and it is now a major approach for the creation of process plasmas, like the one shown below, generated as part of an ORNL-IBM collaboration. The application of ECH to semiconductor processing at ORNL and PPPL has led to new patents. ASTEX, a company formed by fusion researchers from the Massachusetts Institute of Technology, is now one of the leading suppliers of ECH components and systems to both the research and manufacturing communities.

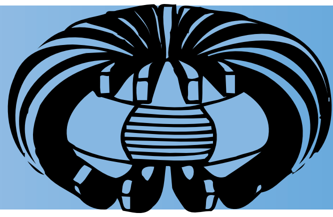
The development of instruments for monitoring and controlling plasma processes, which are essential to enhancing manufacturing capabilities and efficiency, has benefited from techniques developed in fusion research. Examples include Langmuir probes, microwave interferometry, and plasma spectroscopy. Probe hardware and analytical systems, microwave interferometers, and plasma reactors are now commercially available from companies such as Plasma and Materials Technologies, Inc. (PMT), which grew out of the fusion research pro gram at the University of California in Los Angeles.

Close integration of physics and technology, long a hallmark of the fusion program, has characterized the development of plasma production techniques. For example, fusion scientists are working to obtain a detailed understanding of the fundamental chemical and phys ical processes that occur in the plasma and at the location where the plasma interacts with the material surface.

A recent SEMATECH-funded program at Sandia National Labora tories applied a ray-tracing com puter code to the analysis of process plasmas. This code was developed by fusion theorists at ORNL as an aid to understanding fusion plasmas heated by ECH.







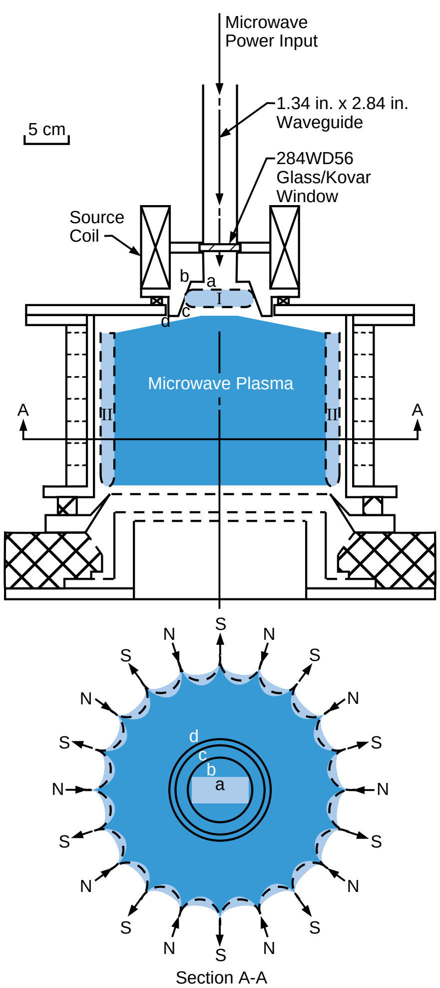
Plasma Production

Growing Diamonds, Reducing Waste

Plasmas can be produced and sustained by directing electromagnetic energy into a gas. Both microwave and radio-frequency (rf) energy have been used for plasma production and heating in fusion experiments. The high-power systems developed for these purposes have been applied to industrial problems outside fusion.

Insights gained from the interaction of hydrogen plasmas with graphite components in fusion devices have been used to develop rf-based systems for creating diamond and diamond-like carbon films. These films have a number of existing and potential applications in electronics and the automotive industry. Plasma processing techniques with manufacturing applications are being developed. High-power rf and microwave heating systems are also being applied to environmental remediation projects.

The use of plasmas has been extended beyond fusion to many other areas, including diamond coatings, new surface cleaning techniques, and solutions to environmental problems.



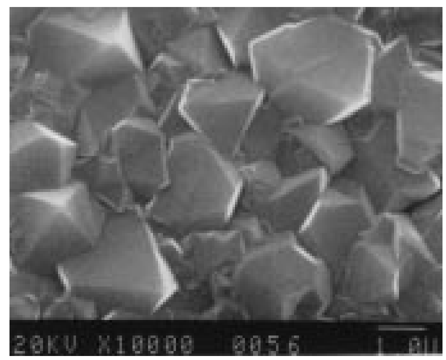
Plasma Generator

When the energetic particles in a fusion plasma strike a solid material, they knock atoms from that material into the plasma. These “impurity” atoms radiate energy away from the plasma and cool it. To minimize this radiation, fusion devices are equipped with graphite structures called limiters and divertors that keep the plasma away from the metal walls of the vacuum vessel.

At Sandia National Laboratories (SNL), fusion researchers studying the interaction of hydrogen plasmas with graphite limiter tiles noted the similarity of carbon-hydrogen films on the tiles to diamond-like carbon (DLC), an amorphous alloy of carbon and hydrogen with properties similar to those of diamonds. They have studied the properties of these films to determine the combination of plasma production techniques and carbon surfaces that yields the best results.

This work has led to the development of DLC coatings with improved adhesion and hardness. Work is under way at SNL on coatings to reduce friction and wear, on improvements in thermal management for electronic packaging, and on innovative diamond-based materials.

At Oak Ridge National Laboratory (ORNL), fusion researchers and other scientists are investigating



diamond film growth as part of a program for fundamental studies of chemical vapor deposition (CVD) materials growth processes. A novel technique for plasma-assisted CVD has been developed, and high-quality diamond films have been produced.

Development of processing techniques, diagnostics, and materials characterization techniques is producing knowledge of molecular dynamics, important process variables, and the relationship of film microstructure to its properties. This information will make it possible to model film growth and optimize film properties.

Using an rf source to produce an oxygen plasma, ORNL researchers have developed a system for removing oil films from the surfaces of manufactured workpieces. This technology, which helps to minimize wastes by removing the need for solvents, has been licensed to SEMATECH.

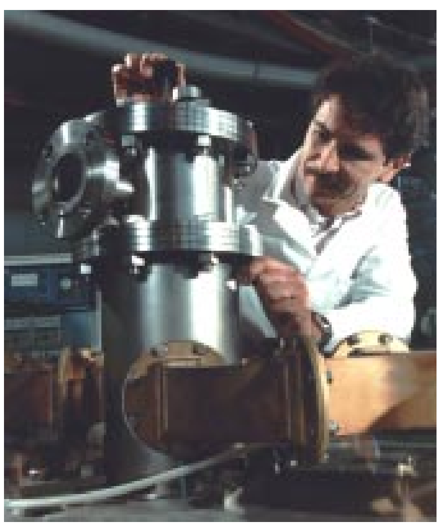
Microwaves are also being applied to the removal of surface contamination from concrete. Microwave energy directed at a concrete surface heats the free water in the concrete matrix. Continued heating produces mechanical stress (induced by steam pressure) that causes the concrete surface to burst, a process known as scabbling. The concrete particles created by this process are small enough to be removed by conventional "vacuum cleaner" systems, but large enough that they do not create a dust problem. A mobile concrete scabbling system, shown above, is under development at ORNL.

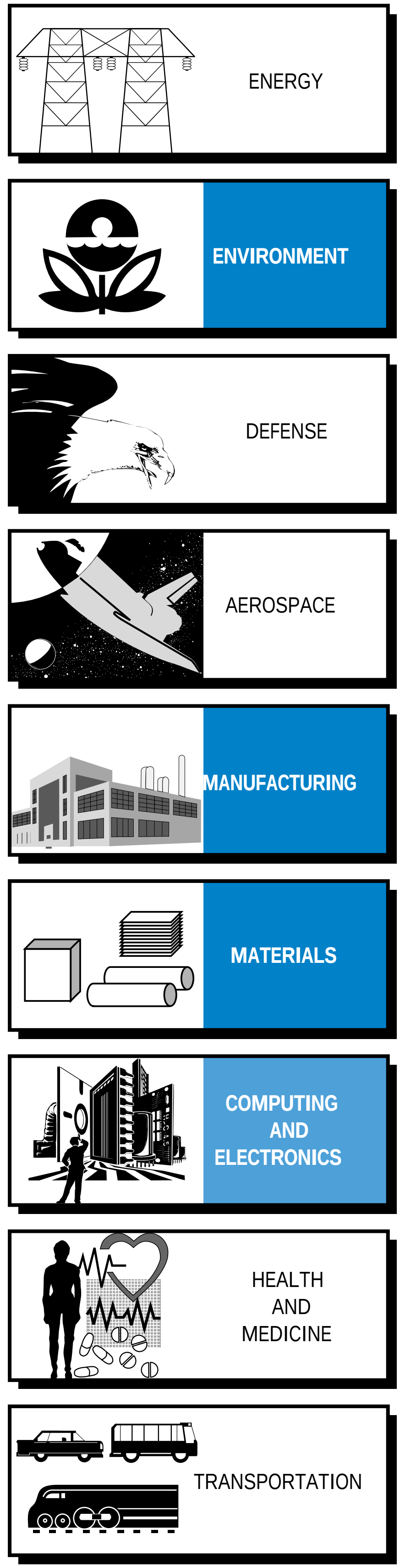
Researchers are adapting rf and microwave sources to other environmental problems. Processing of radioactive waste is an essential ingredient in the Department of Energy's plans to clean up former nuclear sites. These rf and microwave tools can provide safe, cost-effective solutions to a variety of problems.

High-power microwave heating systems like the one shown below are being used to consolidate radioactive waste. Because microwaves heat materials directly, no heating elements or heat transfer surfaces are needed. The number of moving parts can be reduced, so highly reliable, low-maintenance processes can be developed. The microwave generators can be isolated from the radioactive process systems because the microwaves can be transmitted through waveguides.

A wiped-film evaporator that incorporates a 1/3-scale applicator using microwave power has been used to consolidate a surrogate (nonradioactive) slurry at ORNL. Waste treated by this method meets the acceptance criteria for the Waste Isolation Pilot Plant, a federal repository in New Mexico for defense transuranic wastes.

Incinerator ash can be stabilized for long-term storage by means of vitrification—that is, heating it until it melts into a glassy substance. Microwave vitrification of surrogate ash has been demonstrated at ORNL.





Fusion Materials

Material Evidence

Surfaces in a magnetic confinement device that are exposed to the plasma must be able to survive high temperatures, thermal cycling, neutron bombardment, and sputter erosion (which occurs when atoms are dislodged from a surface by collisions with high-energy particles). “Firebricks” that can withstand these conditions are being developed through research aimed at maximizing component lifetimes and minimizing the radioactivity induced by neutrons striking the material that faces the plasma.

This area of fusion research has produced materials and techniques that are being applied or are ready for application to other areas of materials development and analysis, manufacturing, environmental monitoring, and computing and electronics. Applications have also been found in the analysis and authentication of art objects.

Even in a stable, well-confined plasma, there is some interaction between the charged particles in the plasma and the material surfaces surrounding it. In fact, fusion devices make use of these plasma-surface interactions to remove heat introduced into the plasma by auxiliary heating or by fusion reactions, as well as excess fuel particles and helium ash.

The structures that interact with the plasma are called plasma-facing components, or PFCs. Examples include tiles that line the interior of the vacuum vessel, or first wall; limiters, which skim off the outer edge of the plasma; and divertors, which concentrate the flux of charged exhaust particles at the plasma edge onto a small heated region called the strike point. PFCs must withstand harsh conditions, such as high heat fluxes, thermal fatigue, erosion from sputtering or plasma disruptions, loss of coolant accidents, air-steam reactions, and neutron damage. For example, the International Thermonuclear Experimental Reactor (ITER) will include an actively cooled divertor. The divertor target plate must remove a heat flux of up to 10 MW/m^2. For comparison, the heat flux for the interior of a rocket nozzle is about 1 MW/m^2, and that for a missile nose cone during ballistic reentry is 4 MW/m^2.

Fusion researchers are addressing these issues by designing and and building PFCs using materials with low atomic numbers (e.g., beryllium and carbon) to avoid plasma contamination.

The designers for ITER are considering beryllium or carbon fiber composite tiles brazed to a high-strength copper alloy. These duplex structures are being tested extensively in the laboratory. The actively cooled limiter shown at left, which is made of pyrolytic graphite brazed to copper coolant tubes, was designed and built at Sandia National Laboratories (SNL), in collaboration with Oak Ridge National Laboratory, and is now being used on the Tore Supra tokamak in France.

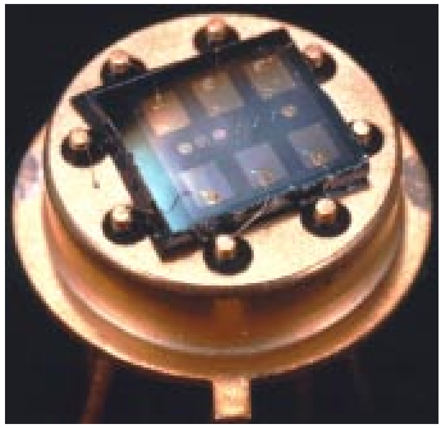
Among the products of PFC research and development are carbon fiber composites that are resistant to thermal shock, plasma spray coatings of beryllium and tungsten, and improved brazing technologies for joining dissimilar materials. Carbon fiber composites whose thermal conductivity at room temperature is twice that of copper have been fabricated. Tungsten plasma spray can produce near-net-shape crucibles for manufacturing applications.

Surfaces that can selectively pump helium while releasing hydrogen were developed as the result of fusion research at SNL. The PISCES plasma arc source, which originated at the University of California in Los Angeles for laboratory simulation of plasma-materials interactions, has been applied to materials processing.

Heat removal technology from PFC development programs includes copper microchannel heat exchangers cooled by helium gas and high-efficiency water cooling structures (hypervapotrons and twisted tape inserts). These programs have also extended the database on thermal fatigue limits and critical heat flux limits to ultrahigh heat fluxes (in the range from 10 to 30 MW/m^2).

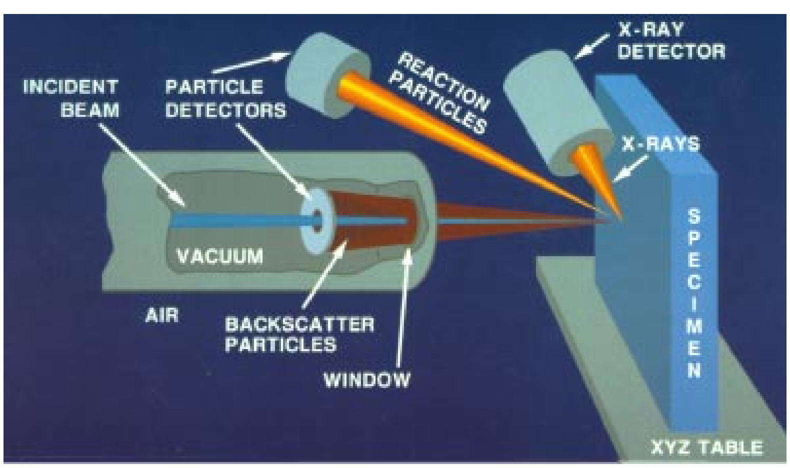
Diagnostics for characterizing the plasma edge and plasma-materials interactions are also being applied outside the fusion program. External ion beam analysis (X-IBA), also developed at SNL, allows for the nondestructive analysis of large components. This technique was used in a forensic study of the gun turret explosion on board the USS *Iowa* and has been transferred to universities, industry, and the international art community. X-IBA techniques, illustrated below, are being applied to analyze hydrogen content in plastic, to study the incorporation of hydrogen isotopes in electrochemical electrodes, and to study the metal content of pigments in paintings at the Louvre.

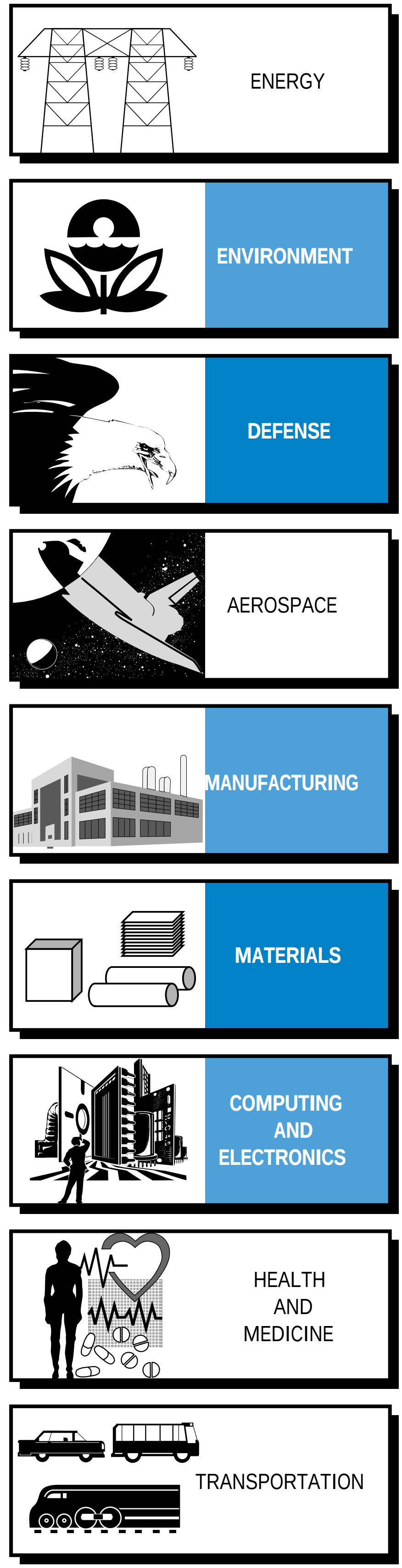
Plasma edge diagnostics such as carbon resistance probes are being applied in semiconductor research, and new hydrogen microsensors are being developed as detectors for flammable gas. These tiny sensors (less than 1 mm^2 in area) are very



sensitive to hydrogen, so they can detect a wide range of gases that contain hydrogen, such as methane, ammonia, and hydrogen sulfide. Work is in progress at SNL to optimize sensor design and electronic circuitry so that these miniaturized sensors, shown above, can be used for environmental monitoring.

Computer codes and modeling techniques developed at fusion institutions for studying plasma-materials interactions are being used in other areas. A code that calculates energetic ion ranges in solids is being used to predict dopant profiles in semiconductor processing. Impurity diffusion codes have found applications in defense and environmental areas. Other codes now under development hold promise for modeling the plasma processing of materials.





ALL-PURPOSE ACCELERATOR

One of the most challenging aspects of fusion engineering is materials development. The energetic neutrons produced by fusion reactions can cause transmutations, heating, and radiation damage in conventional materials.

As part of a program to develop and test materials for fusion, a new concept for a particle accelerator was evaluated, modeled, and constructed. The radio-frequency quadrupole (RFQ) linear accelerator has since evolved into an attractive means of producing ion beams, with extensive applications in high-energy physics research, defense, manufacturing, materials, and health and medicine. It is also being studied as a heating system for future fusion reactors.

The deuterium-tritium (D-T) reaction, which will probably be used by the first fusion reactors, produces intense neutrons, with energies of 14 million electron volts (MeV). To accurately determine the material damage caused by these neutrons, and to develop materials that can resist this damage, fusion scientists have had to find ways of producing a neutron radiation environment similar to that resulting from the D-T fusion reaction.

Particle accelerators increase the kinetic energy of charged particles or ions by accelerating them in an electric field. In a linear accelerator, or linac, the particles are created by a plasma discharge, formed into a beam, and then accelerated through a straight evacuated chamber to bombard a target. By changing the beam energy and the target material, accelerator physicists can create and study a variety of effects. The interaction of the beam and the target can produce the desired neutron radiation for materials testing.

Until 1970, linacs were very large structures that could not efficiently maintain a coherent beam at low kinetic energies. Then a concept was developed in Russia for a linac that uses radio-frequency (rf) voltages to create the electric field for accelerating the particles and quadrupole magnetic fields to focus the beam.

Along its central axis, the rf quadrupole, or RFQ, produces complex, varying electric fields that convert the incoming ion stream into "bunches" of ions. The fields also keep the bunches together while accelerating them.

The photograph at left shows a conventional linac and an RFQ linac (on the table). In addition to being much smaller, the RFQ linac is simple and reliable. It was soon recognized as a useful device that could accept large quantities of low-energy ions and accelerate them to much higher energies. Development work began at Los Alamos National Laboratory in 1977. Modeling and computations were followed by construction of a proof-of-principle device that was demonstrated in 1980.

The RFQ concept can be implemented over a wide range of voltages, frequencies, and physical dimensions, and fusion scientists were among the first to take advantage of these characteristics. An RFQ linac for the Fusion Material Irradiation Test (FMIT) facility was constructed and successfully operated.

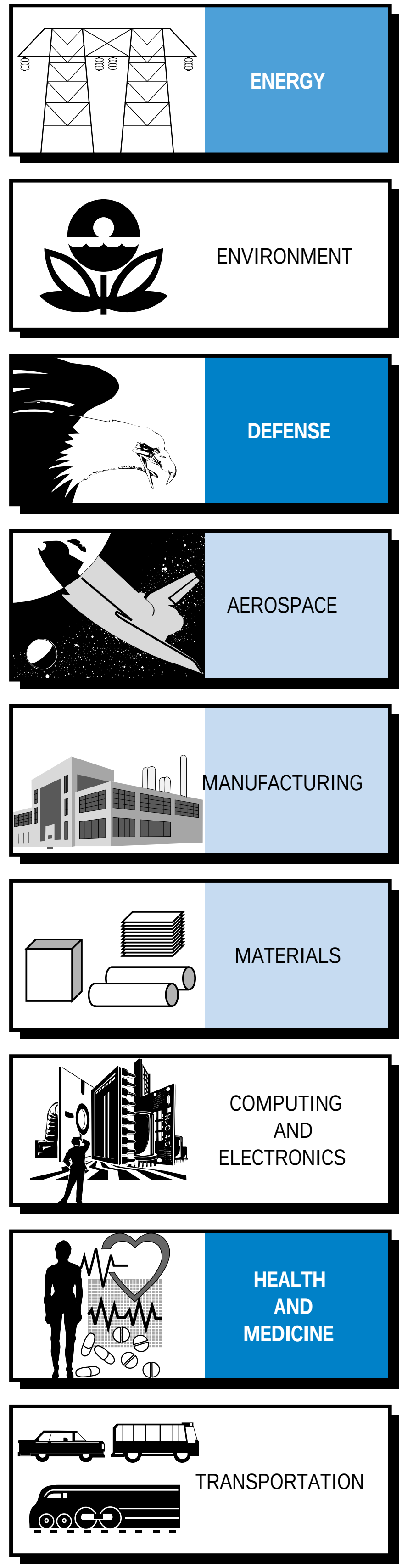
The development work carried out for the FMIT RFQ has paid off in a variety of applications. RFQ linacs are now widely used in physics research, both as the first stage of larger linacs and in experiments to test theories about elementary particles.

With an RFQ as its first stage, a linear accelerator can produce energetic charged particles that are focused into thin beams. Since the beams lose most of their energy in a small volume of tissue, they can destroy the cells in a tumor without damaging the surrounding healthy tissue.

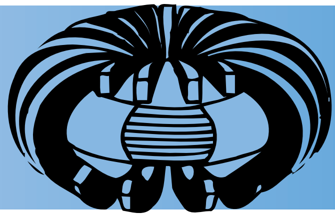
As part of a larger accelerator system, the RFQ is well suited for the production of radioactive isotopes, including radionuclides used in medical diagnostics. The RFQ has also been proposed as the initial stage for linacs producing neutral particle beams for missile defense in space.

As a stand-alone system, the RFQ can produce short-lived medical radionuclides, implant ions into metals and semiconductors, and produce neutron and gamma radiation for materials inspection and research. The RFQ may also provide new ways of applying inspection techniques such as activation analysis, a means of detecting plastic explosives in airline baggage, and neutron radiography, an analysis technique established using neutrons from reactors. Because the RFQ linac is a mobile source of neutrons, it should be a good candidate for extension of this technique to tasks such as inspecting explosive charges in artillery shells, finding cracks and corrosion in aircraft, and analyzing rocket engines during test firing.

The RFQ has been commercialized by AccSys Technology, Inc., a company started by Los Alamos scientists.

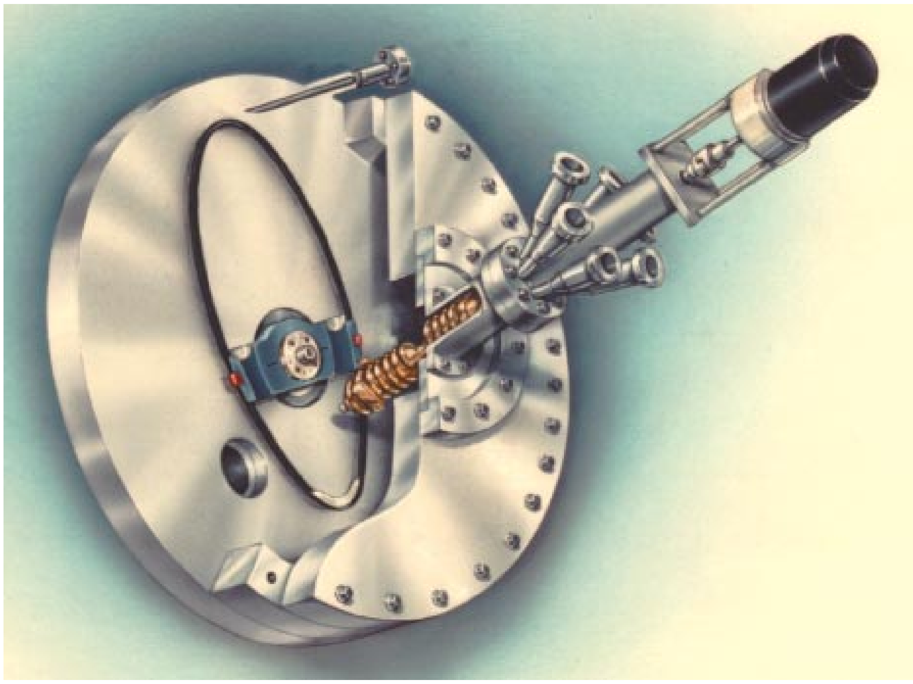


PLASMA FUELING



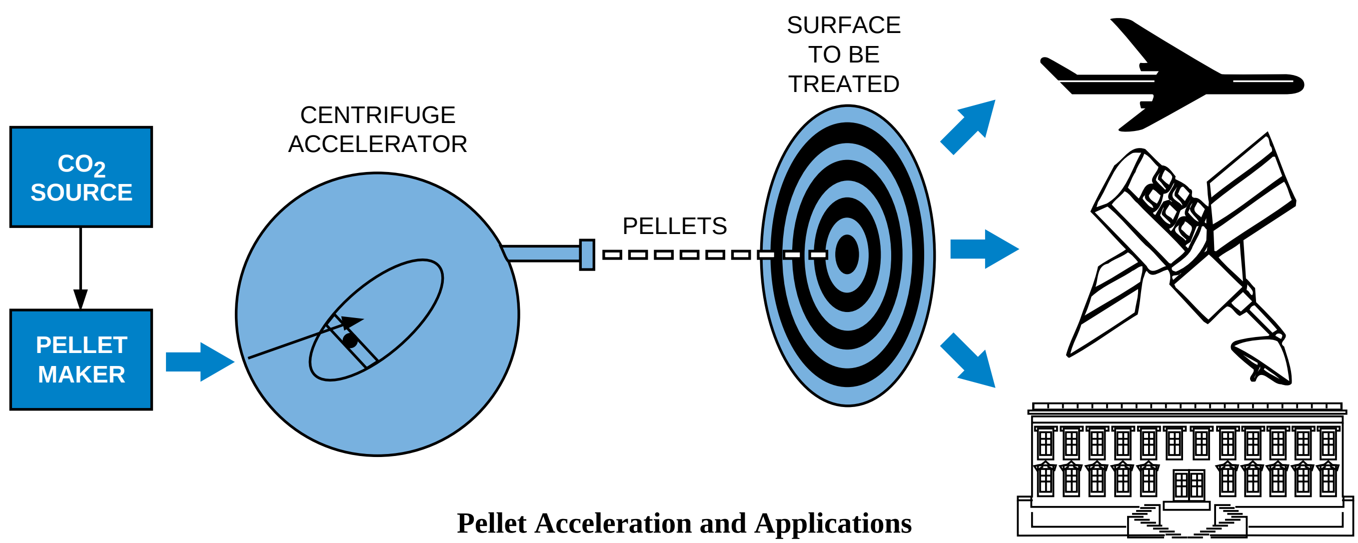
HIGH-TECH HAILSTONES

In a fusion plasma, the initial fuel of hydrogen isotopes is consumed as the fusion process proceeds. Refueling the plasma requires the placement of additional hydrogenic materials deep within the plasma. The most successful method is to inject cryogenic pellets of hydrogen, deuterium, or tritium, accelerated to speeds of more than a kilometer per second. The techniques developed to form and accelerate these small, fast-moving pellets also supply new ways of dealing with problems in defense, aerospace, environmental remediation, and manufacturing.



A stream of cryogenic carbon dioxide pellets traveling at high speeds can be used to remove surface contam-ination by ablation. During this ice blasting process, the pellet material evaporates, separating it from the surface contaminant. Sur face cleaning with practically no unnecessary waste stream is possible.

Cryogenic pellets are produced by freezing the material of choice (typically carbon dioxide or argon) and then chopping the resulting ice into chunks of the appropriate size. Acceleration techniques developed in the Oak Ridge National Laboratory fusion program include the centrifuge accelerator, left, which can inject up to 100 pellets per second, and the pneumatic accelerator, with pellet speeds up to 3000 meters per second.



Pellet Acceleration and Applications

In the centrifuge acceleration technique, pellets are loaded onto a spinning arbor that accelerates them and then slings them off its outer edge at high speeds. Because the size and speed of the pellets can be controlled with great accuracy, the stream of pellets produced can be precisely tailored to create the desired effect.

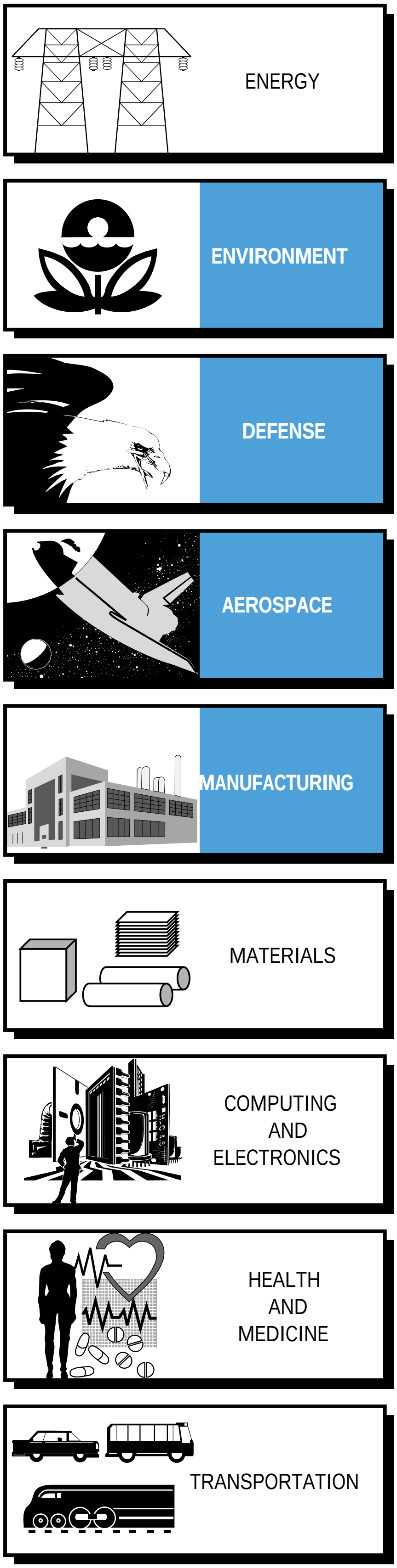
The process resembles sand-blasting, but the accelerated pellets travel at much higher speeds than the particles used in sandblasting (up to 1000 meters per second, compared to about 100 meters per second), and because they are all moving at the same speed, there is much less chance of damaging the material than with conventional processes.

Another advantage is that the pellets simply evaporate into the air. Both carbon dioxide and argon are naturally present in the air, so neither represents an environmental burden. The material removed from the sur face can be collected by conventional "vacuum cleaner" systems.

Applications include the broad area of cleaning materials, including removal of paint, oxide layers, radio -active contaminants, and grease. Conventional means of removing these substances often require the use of solvents that can adversely affect the environment. When surfaces are cleaned with cryogenic pellets, no solvents are necessary.

Argon is especially suitable for use in removing radioactive contaminants because it is an inert gas and does not react chemically with many materials. Thus, the waste disposal problem is limited to the material actually removed—there is no added volume from the removal technique.

Cryogenic pellets are now being tested for removal of paint from Air Force aircraft by Warner Robins Air Logistics Center, as shown below. Other applications of this technique include the use of high-speed pellets to simulate harsh environments. Satellites, rockets, and space platforms undergo collisions with "space debris"—macroscopic and microscopic meteorites, as well as material left behind by earlier space voyages. These collisions can be simu lated in the laboratory by bombarding sample materials with pellets. More generally, studies of erosion and sur face physics can be advanced by use of high-speed pellet technology.



Microwave and RF Heating

Mighty Microwaves

Microwaves can be used for creating fusion plasmas, heating them, and driving electrical currents in them. The capability for producing the high-power microwaves needed for these purposes was created through an intensive development program involving industry, university, and national laboratory researchers. As a result of this program, the United States leads the world in the production of continuous-wave gyrotrons and related equipment. Industry, defense, and scientific research have already benefited from this technology development, and the potential for additional applications is being explored.

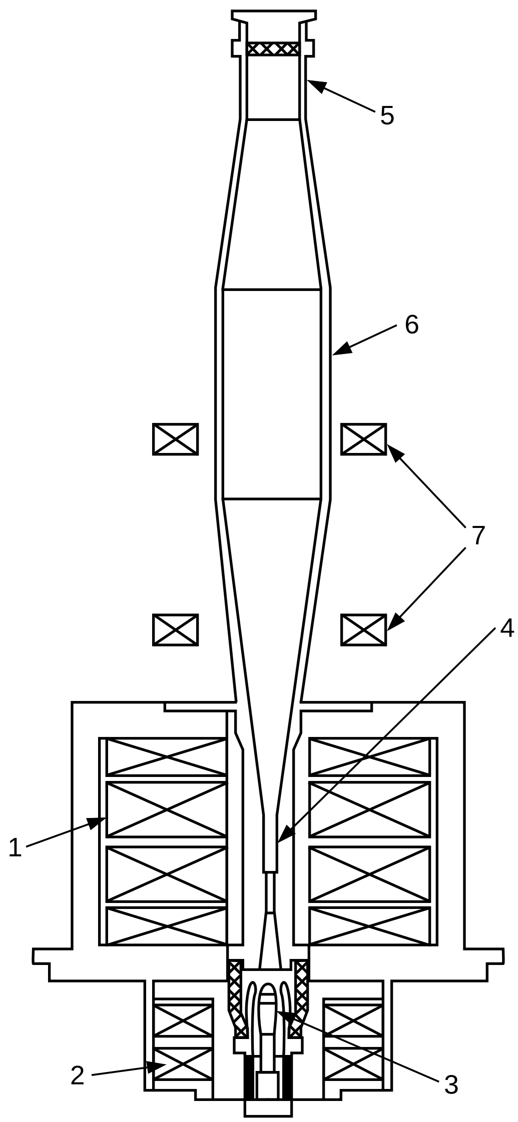
When electromagnetic fields interact with matter, energy is transferred from the fields to the molecular bonds of the matter, causing these bonds to "vibrate." This vibrational energy is dissipated as heat.

Microwaves are a form of electromagnetic energy, with frequencies ranging from 300 MHz to 300 GHz. Depending on the frequency used, microwaves can be used to create a plasma, to heat the ions or electrons in the plasma, or to drive electrical currents in it.

One way to produce microwaves is with a device called a gyrotron, shown at right. Gyrotrons are particularly well suited for applications that involve high-frequency, millimeter-wavelength microwaves, such as radar, satellite links, and medical applications.

Gyrotrons were first developed in the former Soviet Union in the 1960s. As their usefulness for fusion research became apparent, the Department of Energy set up a program for the development of millimeter-wavelength power generators for use in plasma heating systems.

This program, over a number of years, combined basic gyrotron research at the Massachusetts Institute of Technology (MIT) and the Naval Research Laboratory; analytical and material development work by Lawrence Livermore National Laboratory, Oak Ridge



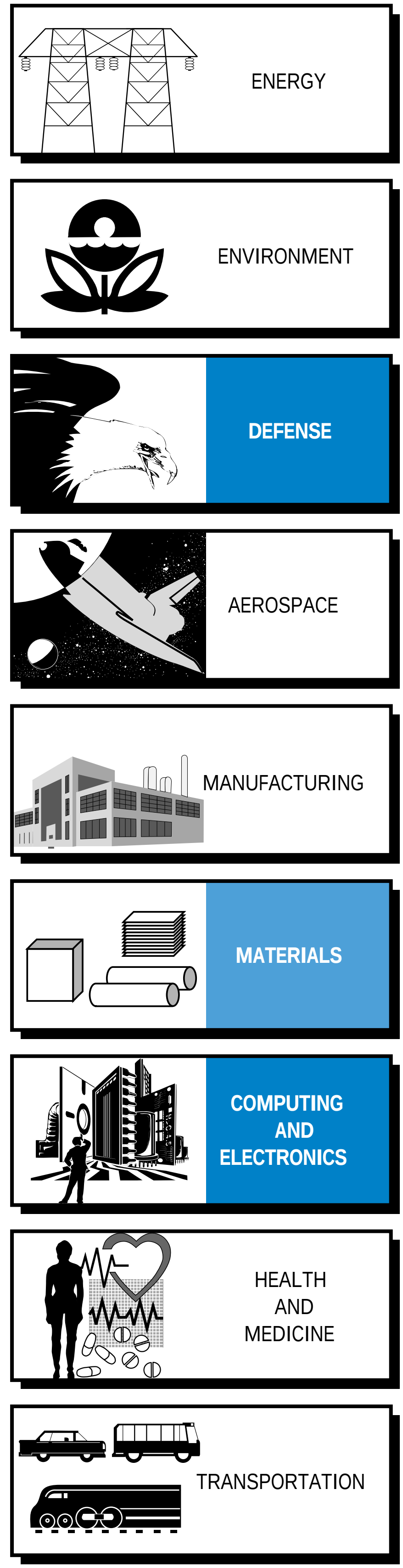
1. Main magnet coils
2. Gun magnet coil
3. Electron gun
4. Cavity
5. Output waveguide and window
6. Beam collector area
7. Collector magnet coils

National Laboratory, MIT, and Rockwell International; and device construction by Raytheon, Varian Associates, Inc., and a division of Hughes Aircraft Company. The aim of the program was to develop continuous-wave (cw) gyrotrons—devices that could produce high power for long periods—and incor porate them into heating systems for fusion devices.

The program has produced a valuable technology base that includes both high-power, high-frequency microwave systems and a cadre of researchers with knowledge in microwave engineering, high-voltage power supply engineering, and microwave physics.

This technology base extends beyond the laboratory to industry. Varian and General Atomics have cooperated in the development and testing of a large, high-power tetrode tube at frequencies over 100 MHz for the JT-60 fusion experiment in Japan.

In materials processing, micro wave sintering, illustrated below, produces high-density, high-strength ceramics. Chemical processing with microwave sources has been used to prepare ultrapure materials by vapor reaction from the walls of the processing chamber. The gyrotron can serve as a widely tunable source for use in high-resolution spectro-scopy, and the gyrotron amplifier has been selected by the Department of Defense for development as a source of high-power radiation for a novel radar system.



Ion and Neutral Beams

Neutral Powers

The problem of heating a fusion plasma to thermonuclear temperatures has been successfully addressed by the development of systems that inject beams of neutral atoms. Neutral particles can be injected into a magnetically confined plasma because they are not affected by the magnetic fields. Once inside the plasma, they ionize and transfer their heat to the plasma.

Neutral beam injection systems have been used on fusion devices for over 30 years, and the ion source and accelerator technologies developed for these systems have led to applications in physics research, environmental studies, defense, aerospace, materials processing, manufacturing, and medicine.

The creation of a neutral beam begins in an ion source like the one shown below that produces a plasma. Ions (charged particles) are extracted from this plasma and accelerated to form a beam. The beam is coupled to a neutralizer, in which most of the ions are converted into energetic neutral particles. The unneutralized (charged) component of the beam is magnetically deflected away, leaving the neutral particles.

In addition to their usefulness in heating a fusion plasma, beams of atoms or molecules moving at high speeds interact with surfaces in several ways. The surface may be etched by physical or chemical reactions with the particles. Thin films may be deposited on the surface or “grown” from chemical reactions between the particles and the surface. Energy may be transferred between the particles and the surface. Ions can be implanted in the surface. The rates at which these interactions with surfaces take place depend on the energy of the particles, which is typically given in millions of electron volts (MeV).

If the ions are to be accelerated to energies of less than 0.1 MeV, positive ions are generated and then neutralized. For energies above 0.1 MeV, it is more efficient to start with negative ions and neutralize them.

The program to develop neutral beams for fusion has produced high -current sources of positive and negative ions of hydrogen and deu terium, the elements of principal interest for fusion applications, and accelerators that can accelerate these beams to energies of 0.1 MeV, with 1.3 MeV a potential development in the future.

Long-pulse positive ion sources were produced by RCA for heating the plasmas in the Tokamak Fusion Test Reactor and the DIII-D tokamak, the lead experiments in the U.S. magnetic fusion program. Related development has led to metal vapor vacuum arc, or MEVVA, sources, which can produce positive ion beams from all solid metallic elements. This type of source, which can be combined with plasma processing, is beginning to find commercial applications. ISM Technologies, Inc., is using these sources to process surfaces for improved resistance to wear and corrosion.

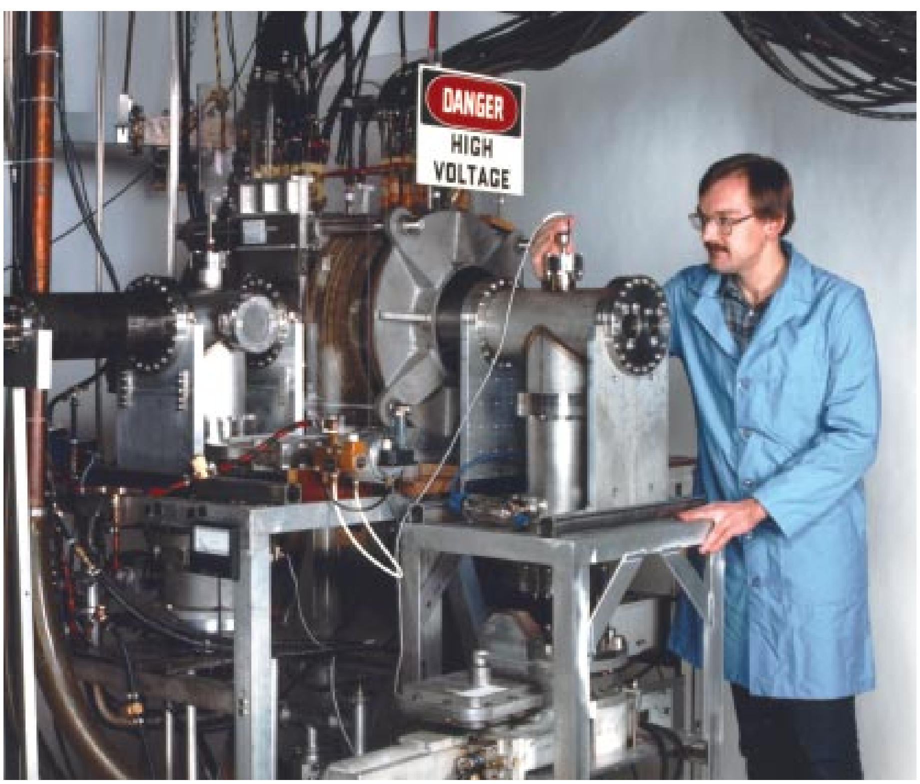
Negative ion sources are also finding applications in areas as diverse as defense, high-energy physics, and medical research. A negative ion source has been supplied to Grumman Aerospace Corporation for the Neutral Particle Beam Program of the Strategic Defense Initiative. Development of a similar source has been funded by the Superconducting Super Collider project. AccSys Technologies, Inc., is building a source designed by Lawrence Berkeley Laboratory for DESY, the German high-energy physics laboratory, and development is under way on a source that will be used for radioisotope tracer studies in environmental and medical research.

A cooperative R&D agreement, or CRADA, has been established to investigate the application of ion implantation in the automotive industry. The CRADA partners are Los Alamos National Laboratory and General Motors.

The surfaces of spacecraft orbiting the earth are eroded by atoms that impinge on them. This erosion, studied in space with the Long Duration Exposure Facility (LDEF) satellite, can be duplicated with neutral beams in the laboratory. In studies at Princeton Plasma Physics Laboratory, funded by the National Aeronautics and Space Administration (NASA), damage suffered by the LDEF during 6 years in orbit was reproduced on the apparatus shown below in less than 40 hours.

NASA is also funding investigations of the application of ion beams to low-damage processing of semiconductor materials. This research, carried out as a collaboration between fusion researchers and IBM, will be applied in the next generation of microelectronic manufacturing.

The use of neutral beams for heating future fusion reactors is being considered. Energies up to 2 MeV will be required, and the accelerator technology to achieve this goal is under development. In conjunction with MEVVA sources, these accelerators will also provide the potential for rapid and efficient processing of bulk materials with large surface areas.

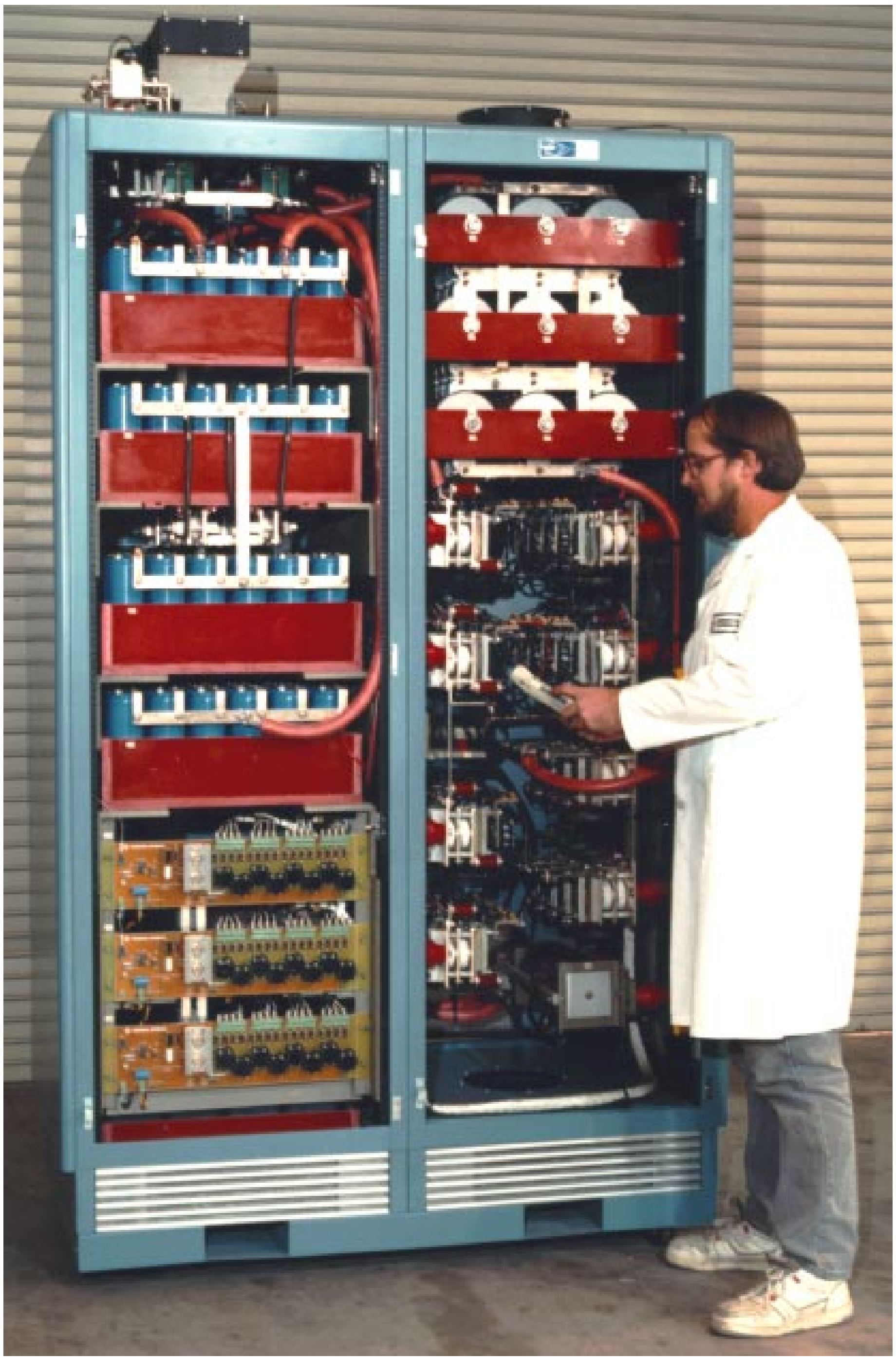


ENERGY
ENVIRONMENT
DEFENSE
AEROSPACE
MANUFACTURING
MATERIALS
COMPUTING AND ELECTRONICS
HEALTH AND MEDICINE
TRANSPORTATION

POWER SYSTEMS

POWER PLAY

Shaping and stabilizing the plasma in a magnetic fusion device is done by changing the currents in the magnetic field coils. Control over these currents required the development of systems capable of handling large amounts of power. Lightweight, compact, and reliable power conversion units have been developed for the fusion program and marketed for applications in defense and transportation.



Technology developed in the fusion program to maintain a stable plasma configuration can be used for efficiently transforming power from ac or dc sources into high currents under accurate control.

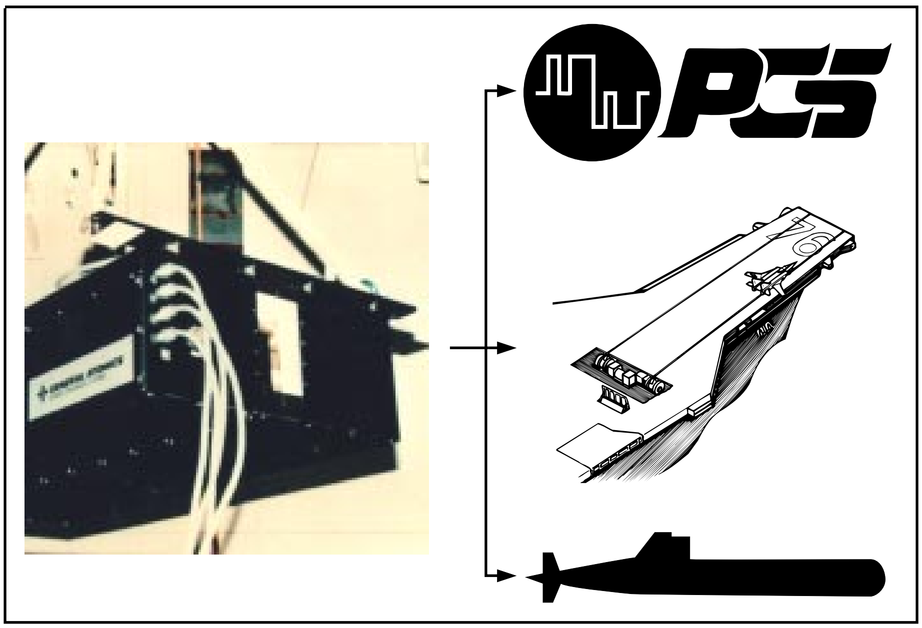
High-current electronic valves that used silicon-controlled rectifier (SCR) switches were developed and used to transform and control more than 100 MW of power in the magnetic field coils of the DIII-D tokamak, thus shaping and stabilizing the fusion plasma. A control system based on these switches was also provided to the Massachusetts Institute of Technology and used for plasma stabilization and control on the Alcator-C tokamak.

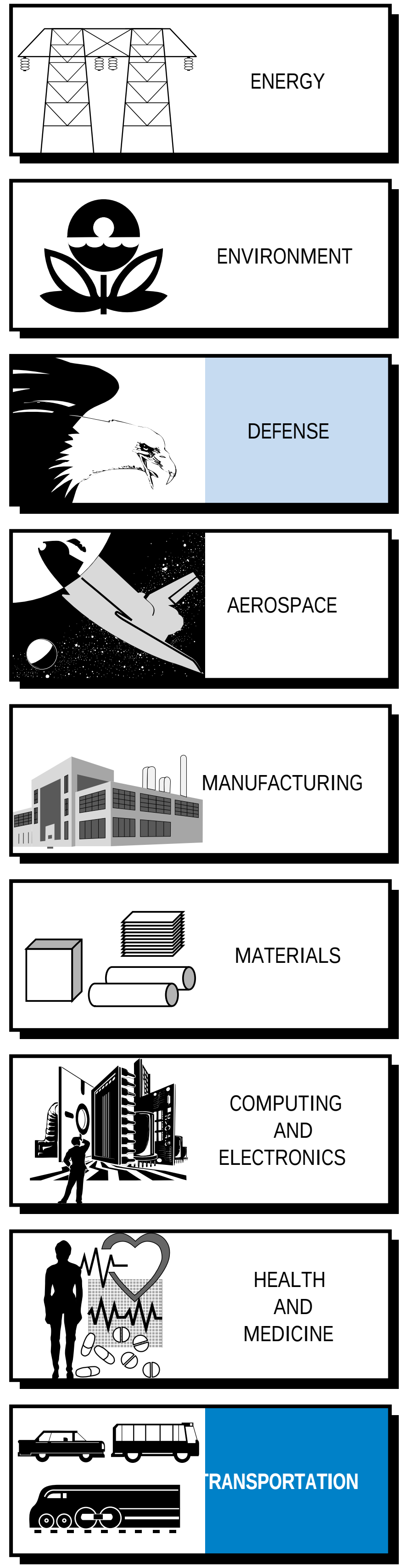
As gate turn-off (GTO) thyristor technology advanced, the power conversion units (PCUs) were improved by replacing the SCRs with GTO thyristors, resulting in more compact, more reliable, integrated units used in the system at left.

The compatibility of PCUs with battery power sources, combined with their attractive weight and size and high reliability, recently led to their incorporation into a conceptual design for a quieter torpedo launcher for the Navy. In this concept, the combination of PCUs and a linear motor replaces the compressed-air-driven water pump now used to launch torpedoes.

The PCU–linear motor combination is also at the heart of ongoing design work aimed at improving Navy aircraft carriers. Although much work remains to be done, the high degree of control inherent in PCUs holds the promise for launch catapults that are superior to the existing steam-driven units. While the pulsed electrical power needed for an individual launch approaches the billion-watt level, the PCUs can tailor the power surge to match different types of aircraft or last-second changes in winds and waves.

The application of PCUs to trans portation needs is being carried out by Power Conversion Systems (PCS), a small company spun off by General Atomics to commercialize the PCU technology. PCS has built a prototype unit to transportation specifications. Production units will be supplied to the Urban Trans-portation Development Corporation of Canada for use in its Advanced Light Rail Transit Mark II railroad cars.

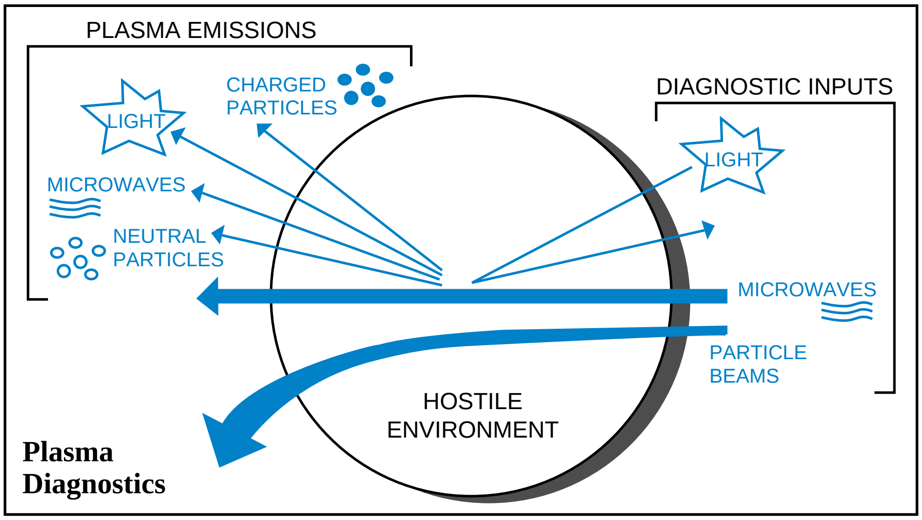




Instrumentation and Measurement

Diagnostic Development

Understanding the behavior of a fusion plasma has required the development of instruments and techniques for measuring the plasma parameters. The development of these "diagnostics," which must be able to tolerate the hostile environment created by the high temperatures and energetic particles in the plasma, has led to advances in detector and laser technology, with applications in energy conservation, aerospace, manufacturing, and health and medicine.



A hydrogen plasma glows with a bright reddish-purple color. Looking at this visible light is one way to determine what is happening in a plasma. Fusion researchers also use electromagnetic radiation with wavelengths both longer and shorter than those of visible light to "look" at plasmas.

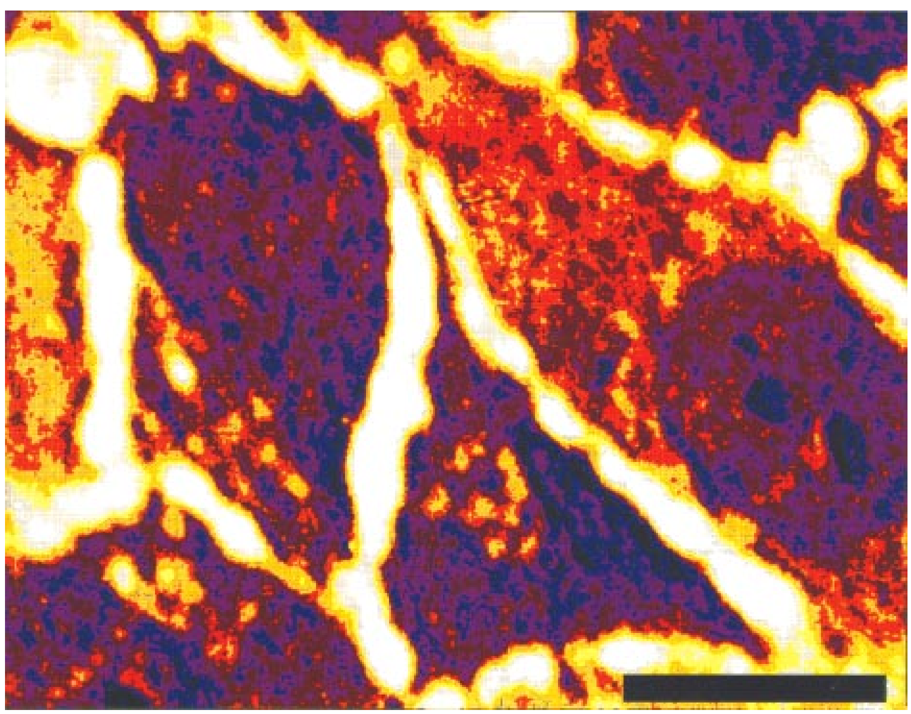
The light, microwaves, and particles that are emitted by the plasma are measured using cameras, spectrometers, particle analyzers, and other specialized instruments. Fast reciprocating probes, laser beams, particle beams, and microwaves are used to make active measurements.

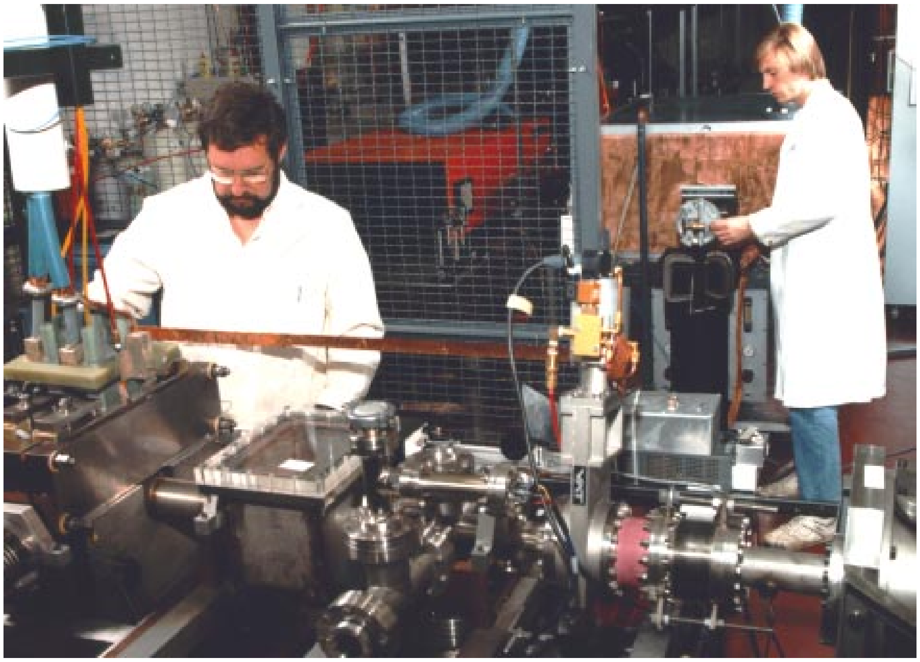
Techniques developed to monitor the position of the plasma in a fusion device have been incorporated into boiler imaging pyrometers that continuously measure the flame temperature in fossil-fuel power plants. Plant operators save energy by precisely controlling the oxygen and fuel mix for optimum efficiency. This system was developed by Princeton Plasma Physics Laboratory (PPPL) for Public Service Electric and Gas Corporation.

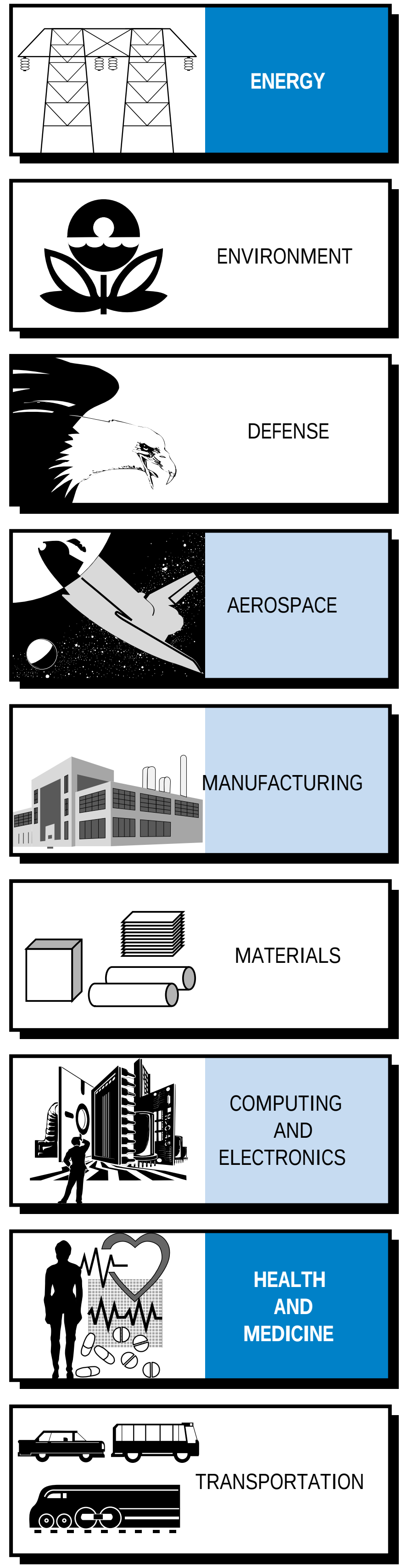
Lasers are valuable in measuring a variety of plasma parameters, and a new type of laser with medical and manufacturing applications has been developed as the direct result of fusion research.

In 1976, as the result of work on a fusion experiment called the Floating Multipole, it was theorized that a plasma could serve as a medium for soft X-ray lasing action. (Here "soft" refers to the ability of the X rays to penetrate the medium through which they pass.) In 1984, PPPL scientists successfully demonstrated X-ray lasing at at a wavelength of 18.2 nanometers (nm).

The soft X-ray laser (SXL) is now being applied to microscopy.







X-ray microscopy bridges gaps in present technologies because it provides better resolution than optical microscopy and, unlike electron microscopy, allows the examination of live biological specimens. These characteristics make it a valuable tool for medical researchers studying cells like the cancer cell at left.

In soft X-ray contact microscopy, samples are placed in contact with a high-resolution recording medium and exposed to X rays. When the medium is developed, a replica of the sample is produced and can be examined with an electron microscope. A new soft X-ray imaging microscope now being developed will produce an image on a television monitor.

Because most applications require X rays with wavelengths shorter than 18.2 nm, a two-laser approach to producing X-ray lasing action at shorter wavelengths is being explored on the system shown above. One laser produces the plasma column, while a second laser produces shorter-wavelength X-ray emission. This high-power laser uses ultrashort ultraviolet laser pulses, allowing extremely high focused power (about 10^{18} watts per square centimeter) with only modest energy. Wavelengths of 1 to 3 nm should be achievable.

The techniques being developed for contact microscopy are closely related to those of microlithography—used for “printing” integrated circuit patterns on semiconductors. The high-resolution X-ray laser could allow a 100-fold increase in the number of components on a single chip.

In collaboration with Princeton Instruments, Inc., PPPL researchers are exploring the application of charge-coupled devices (CCDs) to the direct imaging of soft X rays. Specialized thin-backed CCDs are being tested to determine whether they are sensitive to soft X rays. Incorporating the high sensitivity afforded by CCD imaging into soft X-ray instruments would enhance the effectiveness of these new instruments in a host of applications, including plasma diagnostics, material analysis, X-ray astronomy, and X-ray microscopy.

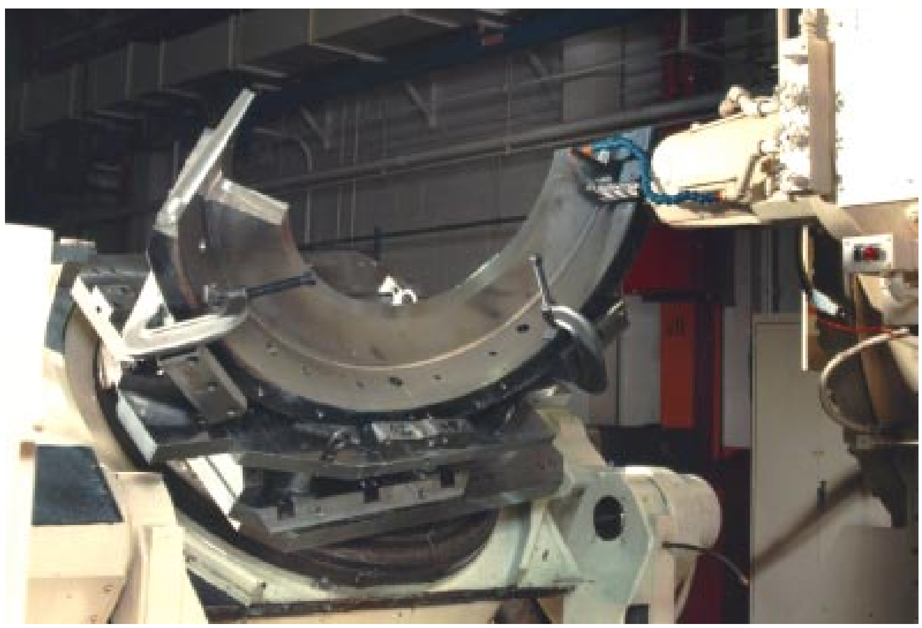
Fusion Theory and Computing

Number Crunching

The behavior of a fusion plasma is extremely complicated. A plasma can exert pressure against the confining magnetic field, carry currents, oscillate, radiate energy, undergo particle loss, or become unstable. Understanding this behavior is the province of fusion theorists, who explore the physics of plasmas and also develop and use computational tools for analysis and modeling and for optimizing the configurations of fusion devices.

In their quest for powerful computing technology and computational techniques, fusion researchers have both helped to develop and benefited from advances in supercomputers, parallel processing, and high-speed computer networks. Computer codes, numerical techniques, and engineering applications developed for fusion are being used to examine a wide variety of problems, including precision construction, the national air traffic control system, and global warming. Visualization techniques are being applied to every field that relies on computer calculations and data analysis.

The National Research and Education Network, mandated by the High Performance Computing and Communications Act of 1991, has its roots in the national computer network originally developed to support centralized supercomputing for fusion research. As part of this initiative, the fusion program has been instrumental in establishing links between the big science at national laboratories and the teachers and students of high school and college science and mathematics.



Models of plasma behavior have produced new understanding of phenomena outside fusion. For example, the ability to model the dynamics of turbulent flows, which is critical to controlling a fusion plasma, is also a key to the prediction of global climate changes. These problems are being addressed with the new supercomputers and massively parallel computers. Work to help users interpret the meaning of the vast amounts of data available from these computers has produced visualization hardware and software.

Fusion researchers have assisted the Federal Aviation Administration in developing methods for analysis and real-time modeling of the national air traffic control system. The ability to analyze system loading and its anomalies will improve the ability to deal with changing traffic loads, weather-related delays, or other problems.

Fusion experimental devices require precision measurement and engineering techniques to ensure that they will operate as planned. Computational methods have been developed to support these requirements and applied to the characterization, measurement, and positioning of components for other complicated systems.

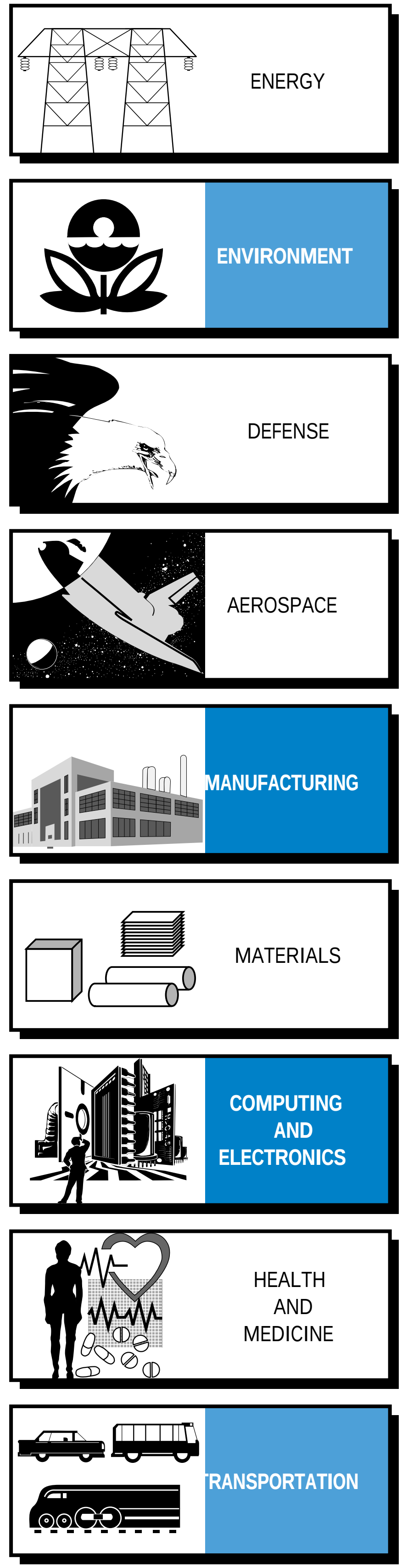
A virtual reference technique was developed at Oak Ridge National Laboratory to allow machining of complicated castings with no reference surfaces on a five-axis, numerically controlled milling machine, shown above. Virtual reference points, calculated and represented by tooling balls, are used to define a casting's position. The milling machine is then programmed with these definitions so that the casting can be machined without being repositioned. These techniques have been used to measure castings for the armed forces and are available for industrial applications.

Computer-based process control and data acquisition systems are a key element in the successful operation of complicated systems. Software that allows real-time initiation and control of processes at remote sites is being used on many systems outside fusion. This software, which allows personnel at one site to control and adjust systems at another location, will make "telecommuting" easier. It was made possible by advances in computer networking—the linking of computers at many sites via telephone systems, satellites, and optical cables.

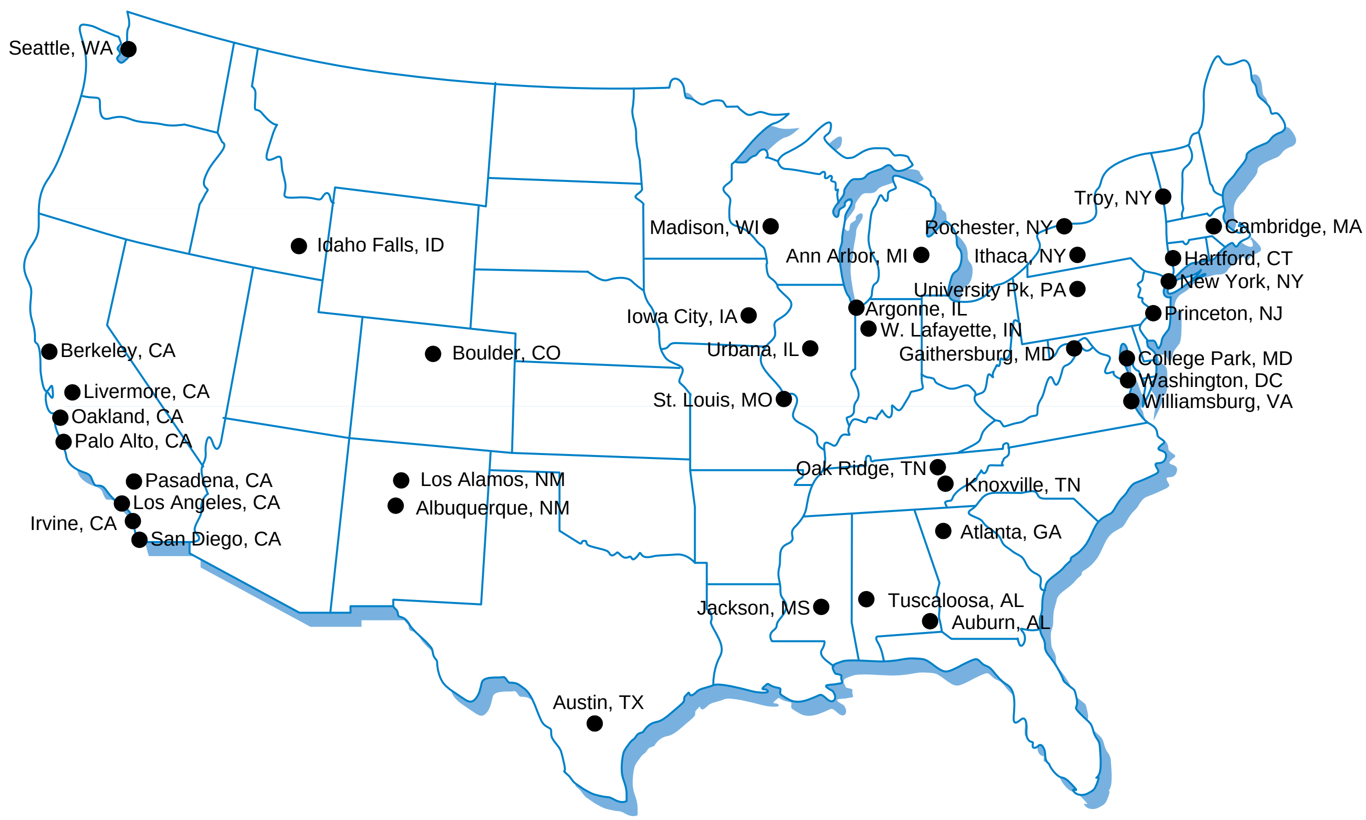
Fusion research has been at the forefront of networked computing since 1974, when the Department of Energy initiated a national computer network for fusion research. The Controlled Thermonuclear Research Computer Center, established in 1974 to meet the computational demands of the national magnetic fusion energy program, was a pioneer in providing centralized supercomputing via network access.

Today, as the National Energy Research Supercomputer Center (NERSC), this center serves both fusion and a number of other energy research programs and is a valuable educational resource. NERSC administers the Energy Sciences Network (ESnet), a nationwide computer data communications network that provides supercomputing resources to and connections among researchers at national laboratories, universities, private laboratories, and industrial organizations involved in energy research. It is also the home of the National High School Supercomputer, a single-processor CRAY X-MP that is being made available by NERSC, the Department of Energy, and Cray Research, Inc., to use supercomputing as both a teaching tool and a catalyst to spark student interest in science and mathematics.

The national High Performance Computing and Communications Initiative calls for the establishment of a National Research and Education Network (NREN) that will be hundreds of times faster than today's networks. Through ESnet, the Department of Energy is responsible for implementing the emerging technologies to support the desired data transmission rates of close to one billion bits per second. With the networks of NASA and the National Science Foundation, ESnet will serve as the backbone for the NREN.



Major Sites of U.S. Fusion Research



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